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Forensic DNA Interpretation and Human Factors: Improving Practice Through a Systems Approach

Report of the Expert Working Group on Human Factors in Forensic DNA Interpretation

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HUMAN FACTORS in Forensic DNA Interpretation

NIST NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY U.S. DEPARTMENT OF COMMERCE

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NIST Interagency Report
NIST IR 8503

Forensic DNA Interpretation and Human Factors: Improving Practice Through a Systems Approach

The Expert Working Group on Human Factors in Forensic DNA Interpretation

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May 2024

U.S. Department of Commerce
Gina M. Raimondo, Secretary

National Institute of Standards and Technology
Laurie E. Locascio, NIST Director and Under Secretary of Commerce for Standards and Technology

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Abstract

The study of human factors in forensic science informs our understanding of the interaction between humans and the systems they use. The Expert Working Group (EWG) on Human Factors in Forensic DNA Interpretation used a systems approach to conduct a scientific assessment of the effects of human factors on forensic DNA interpretation with the goal of recommending approaches to improve practice and reduce the likelihood and consequence of errors. This effort resulted in 44 recommendations. The EWG designed many of these recommendations to improve the production, interpretation, evaluation, documentation, and communication of DNA comparison results. Additional discussions include:

- The potential for cognitive bias and how to reduce it.
- DNA transfer, persistence, prevalence, and recovery.
- Work environments and how they can impact productivity and morale.
- Building a more equipped workforce through investment in centralized forensic education and training.
- How forensic science service provider management and leadership can foster a culture where errors are seen as a learning opportunity and not treated punitively.
- Future research and funding directions in forensic DNA interpretation.

This report serves to educate both forensic science service providers and criminal justice partners (e.g., legal practitioners, law enforcement investigators, parent organization leadership, forensic science educators).

Keywords

cognitive bias; error; forensic DNA interpretation; forensic science service provider; hierarchy of propositions; human factors; laboratory management; likelihood ratio; probabilistic genotyping software; quality assurance; systems approach; task-relevant information; testimony; training.

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Glossary

Terms included in the Glossary appear **in bold** on their first use in the text. Of relevance to the study of human factors: words can be interpreted, comprehended, or understood differently due to worldview, familiarity, convention, and other factors. When multiple terms are in use for the same or similar concepts, the Expert Working Group (EWG) on Human Factors in Forensic DNA Interpretation chose one for consistency. In other instances, a new term that better reflects the intended meaning is introduced.

A

Activity-Level Propositions: Statements that are formulated to help answer questions related to disputed activities and the presence or absence of biological material.

Administrative Supervisor: One of two primary forensic science service provider (FSSP) leadership and managerial positions in an FSSP's DNA section. An Administrative Supervisor focuses largely on case management, budgeting, managing personnel, addressing the FSSP's backlog, and the overall quality of the final product produced by the FSSP.

Align: A term signifying that a DNA profile from a known sample is compatible with the profile (or part of the mixture profile) from a questioned sample. Substantively equivalent terms are "included," "consistent with," and "match."

Allele: In classical genetics, an allele is one of several alternative forms of a gene. Alleles are inherited separately from each parent, and for a given gene, an individual may have two different alleles (heterozygosity) or the same allele (homozygosity). In forensic DNA analysis, the term is applied to any DNA region used for analysis (e.g., a short tandem repeat [STR] location or a gene location).[1]

Allele Frequency: Because nearly all human beings have two sets of chromosomes, a sample (or a population) of N individuals has a pool containing approximately 2N alleles per locus. The proportion of times that any particular allele occurs in this allele pool is the (relative) frequency of the allele.

Allelic Drop-Out: Failure to detect an allele within a sample or failure to amplify an allele during polymerase chain reaction [PCR]; due to primer binding site mutations or stochastic effects when attempting to amplify low amounts of DNA template.[2]

Applied Research: Research that uses scientific knowledge to develop practical solutions to operational challenges.

[1] Kaye DH, Sensabaugh G. Reference Guide on DNA Identification Evidence. *Reference Manual on Scientific Evidence*. 3rd ed. The National Academies Press: Washington, DC, 2011. doi:10.17226/13163.

[2] Butler JM. *Fundamentals of Forensic DNA Typing*. Elsevier Academic Press: San Diego, CA, 2009. doi:10.1016/C2009-0-01945-X.

Audit: A systematic, independent, documented process for obtaining records, statements of fact, or other relevant information and assessing them objectively to determine the extent to which specified requirements are fulfilled.[3]

B

Binary Method: A DNA comparison or interpretation method where inferred genotypes are either included or excluded from the profile using a stochastic threshold and other variables such as heterozygote balance, mixture ratio, and stutter ratio.[4] It is sometimes referred to as the *manual method*.

C

Capillary Electrophoresis (CE): An analytical technique that uses an electric field to separate DNA molecules by their size based on migration through a narrow glass capillary tube filled with a liquid polymer.[5]

Case Management: The review, prioritization, and assignment of cases to the DNA workflow.

Cognitive Bias: The class of cognitive effects through which an individual's preexisting beliefs, expectations, motives, or the situational context may influence the collection, perception, and interpretation of information, or resulting judgments and decisions, without the individual being consciously aware of this influence.[6]

Combined Probability of Inclusion (CPI): The probability that, in a given population, a randomly selected, unrelated individual would be included as a potential contributor to the observed mixture profile.

Confirmation Bias: The process through which preexisting beliefs or expectations frame a person's perception, search for, and interpretation of other information in ways that support their preexisting view.[7]

Contextual Bias: A deviation in human judgment caused by exposure to information that is either irrelevant to the judgmental task or inappropriate for consideration.[8]

Contextual Information Management (CIM): A part of case management that minimizes analysts' exposure to task-irrelevant information while ensuring that all task-relevant information is available to the analyst.

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[3] International Organization for Standardization (ISO). *Conformity Assessment: Vocabulary and General Principles, ISO/IEC 17000:2020* 2004. https://www.iso.org/standard/73029.html.

[4] Coble MD, Bright JA. Probabilistic Genotyping Software: An Overview. *Forensic Science International: Genetics*. 2019; 38:219-24. doi:10.1016/j.fsigen.2018.11.009.

[5] Butler JM. *Fundamentals of Forensic DNA Typing*. Elsevier Academic Press: San Diego, CA, 2009. doi:10.1016/C2009-0-01945-X.

[6] Kassin SM, Dror IE, Kukucka J. The Forensic Confirmation Bias: Problems, Perspectives, and Proposed Solutions. *Journal of Applied Research in Memory and Cognition*. 2013; 2(1):42-52. doi:10.1016/j.jarmac.2013.01.001; Spellman BA, Eldridge H, Bieber P. Challenges to Reasoning in Forensic Science Decisions. *Forensic Science International: Synergy*. 2022; 4:100200. doi:10.1016/j.fsisyn.2021.100200.

[7] Nickerson RS. Confirmation Bias: A Ubiquitous Phenomenon in Many Guises. *Review of General Psychology*. 1998; 2(2):175-220. doi:10.1037/1089-2680.2.2.175.

[8] Organization of Scientific Area Committees (OSAC). *OSAC Preferred Terms*. 2023. https://www.nist.gov/system/files/documents/2023/07/21/OSAC%20Preferred%20Terms_July%202023.pdf.

Criminal Justice Partner: An entity or individual, such as a law enforcement investigator, defense attorney, judge, or prosecutor, who commonly interacts with, uses, or supports the work completed by an FSSP.

Customer: The entity or individual who has requested forensic science services.

D

Deconvolution: Interpreting allelic information (e.g., size and height) to generate a list of possible genotype combinations that might explain a mixture profile. This can be done manually or with the aid of software.

Developmental Validation: The acquisition of test data and determination of conditions and limitations of a new or novel DNA method for use on forensic samples. [9] Usually conducted by the vendor of the application/technology.

Direct-to-DNA: A DNA casework approach that removes serology as the initial screening of a sexual assault kit sample. Instead, DNA quantification is used as the initial screening to determine the ratio of male to human DNA to inform downstream processing. This approach is also known as *Y-screening*.[10]

Deoxyribonucleic Acid (DNA): The genetic material of organisms; a class of nucleic acids identified by the presence of deoxyribose, a sugar, and the four nucleobases, adenine, thymine, cytosine, and guanine.[11]

DNA Analysis: The process of examining biological evidence in criminal matters using DNA technologies, including DNA isolation and purification methods, data interpretation, statistical analysis, report writing, and courtroom testimony.[12]

DNA Analyst: An individual who has completed training requirements for casework sample analysis, passed a competency test, and is subject to a proficiency testing program. This individual can conduct or direct the analysis of forensic samples, interpret data, reach conclusions, and generate reports. This definition includes both individuals who process the DNA samples and those who perform the statistical analysis and interpretation of the DNA results.

DNA Comparison: An examination of the similarities and differences in DNA extracted from two or more samples.

DNA Expert: An individual presenting testimony in court who has scientific or technical knowledge in DNA analysis.

DNA Interpretation: The process of evaluating DNA data for ascertaining genotypes. Aspects of the interpretive process can include making assumptions or inferences about the number of contributors; distinguishing between alleles and artifacts; assessing possible degradation,

[9] Federal Bureau of Investigation (FBI). *Quality Assurance Standards for Forensic DNA Testing Laboratories*. 2020. https://le.fbi.gov/file-repository/forensic-qas-070120.pdf/view.

[10] Forensic Technology Center of Excellence (FTCoE). *User Guide: Cost-Benefit Analysis Tool for Labor Expenditure Associated with Sexual Assault Kit Processing Workflows*. 2022. https://forensiccoe.org/private/6317b48de9b72.

[11] Butler JM. *Fundamentals of Forensic DNA Typing*. Elsevier Academic Press: San Diego, CA, 2009. doi:10.1016/C2009-0-01945-X.

[12] American National Standards Institute/Academy Standards Board. *ANSI/ASB Standard 022: Standard for Forensic DNA Analysis Training Programs*. 2019. https://www.aafs.org/sites/default/files/media/documents/022_Std_e1.pdf.

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inhibition, and stochastic effects; and determining whether the data are suitable for comparison.[13]

DNA Results: Measurements or inferences from the analytical process, including estimating the amount of DNA in a sample, ascertaining suitability for comparisons, comparing data from a pair of samples, and assigning a statistical value (e.g., likelihood ratio [LR], Random Match Probability [RMP]).

E

End-User: Anyone who uses a DNA report for the purpose of informing an action or decision. End-users can include DNA analysts, law enforcement investigators, attorneys, defendants, complainants, court personnel, judges, and jurors.

F

Factfinder: The person or people who have been tasked with appraising the facts that underlie a particular matter in a case. The judge or jury is the factfinder in criminal trials.

Forensic Profile: Sometimes referred to as a *forensic unknown profile*, it is a DNA profile derived from the analysis of a trace or item collected as part of a criminal investigation that has an unknown or questioned origin.

Forensic Science Service Provider (FSSP): An agency or individual providing forensic science services.[14]

Foundational Research: Research that focuses on expanding the understanding of fundamental concepts and theories, often without immediate practical application.

H

Heuristics: Cognitive shortcuts or rules-of-thumb for making decisions or judgments.[15]

Hierarchy of Propositions: A framework to help analysts formulate propositions at a level that is appropriate for the issue(s) at hand. Propositions can be classified into five levels: offense, activity, source, sub-source, and sub-sub-source.

[13] Organization of Scientific Area Committees (OSAC). *Standard for Interpreting, Comparing and Reporting DNA Test Results Associated with Failed Controls and Contamination Events, Version 2.0. OSAC Proposed Standard 2020-S-0004*. May 19, 2023, 2021. https://www.nist.gov/system/files/documents/2021/06/01/OSAC%202020-S-0004_Standard_for_Interpreting_Comparing_and_Reporting_DNA_Test_Results_with_Failed_Controls_and_Contanimation%20FINAL%20OSAC%20PROPOSED.pdf.

[14] National Commission on Forensic Science. *Views of the Commission: Defining Forensic Science and Related Terms*. 2016. https://www.justice.gov/sites/default/files/ncfs/pages/attachments/2015/04/16/final_draft_for_ncfs_vote-defining_forensic_science_and_related_terms.pdf.

[15] American Psychological Association. Particularly Exciting Experiments in Psychology - Heuristics. Accessed March 23, 2024. https://www.apa.org/pubs/highlights/peeps/issue-105.

I

Internal Validation: Experiments performed at a particular laboratory to determine how well a method already established as valid performs when applied to casework-like samples within that laboratory.

L

Likelihood: In statistics, the conditional probability of data given a hypothesis (or this probability multiplied by an arbitrary constant). Colloquially, a synonym for "probability."

Likelihood Ratio (LR): A measure of the relative strength of support that particular findings give to one proposition against a stated alternative.[16] It is defined in terms of the ratio of two conditional probabilities: (i) the probability of the findings given that one proposition is true and given the conditioning information; and (ii) the probability of the findings given that the other proposition is true and given the conditioning information.

Linear Sequential Unmasking: A contextual information management approach in which an analyst performs their analysis of the sample before being exposed to the reference material. It is designed to minimize cognitive bias.

Locus: A location in the genome, that is, a position on a chromosome where a gene or other structure begins.

O

Outcome Error: An error in the final opinion or result.

P

Person of Interest (POI): Although sometimes used to infer a suspect, it is any individual (e.g., suspect, victim, complainant, candidate) who is considered as a potential source of material recovered in the context of a crime, paternity, or a missing person case. Material from or belonging to this individual can then be compared with the material of a known or unknown source.

Posterior Odds: The odds in favor of one proposition relative to another (non-overlapping) proposition formed after considering the effect of the data on one's prior odds.

Prior Odds: The odds in favor of one proposition relative to another (non-overlapping) proposition before considering the DNA data.

Probabilistic Genotyping: In traditional, binary matching, every genotype is said to match with a probability of 0 or 1, and a likelihood ratio (or Random Match Probability) for the single matching genotype (or single set of genotypes in a mixed profile) is assigned. Probabilistic genotyping

[16] Aitken C, Berger CEH, Buckleton J, Champod C, Curran JM, Dawid AP, Evett IW, Gill P, Gonzalez-Rodriguez J, Jackson G, Kloosterman A, Lovelock T, Lucy D, Margot P, McKenna L, Meuwly D, Neumann C, Daeid NN, Nordgaard A, Puch-Solis R, Rasmusson B, Redmayne M, Roberts P, Robertson B, Roux C, Sjerps MJ, Taroni F, Tjin-A-Tsoi T, Vignaux GA, Willis SM, Zadora G. Expressing Evaluative Opinions: A Position Statement. *Science & Justice*. 2011; 51(1):1-2. doi:10.1016/j.scijus.2011.01.002; Aitken C, Taroni F. *Statistics and the Evaluation of Evidence for Forensic Scientists*. 2nd ed. John Wiley & Sons, Ltd: West Sussex, UK, 2004. doi:10.2307/1268932.

allows for the possible genotypes to give rise to the data with probabilities between 0 and 1. It uses statistical modeling to compute these genotype-to-data probabilities. Likelihood ratios are reported for the possible genotypes (or combinations of genotypes that could be in a mixed profile).[17]

Probability: Numbers between zero and one that indicate the chance of the possible outcomes of events and that conform to a small number of mathematical axioms and definitions. In principle, probabilities can be used to quantify degrees of belief in the truth of propositions.

Probative Value: The tendency for a piece of evidence to support a given proposition. This is not intended to refer to the legal assessment of probative value that is done in accordance with the rules of evidence and case law.

Process Error: An error that occurs in any step prior to the output of a result.

Process Map: A workflow diagram of a process or a series of parallel processes.

Proposition: A statement that is either true or false. In the context of evidence evaluation, propositions should be formulated in pairs: the paired propositions should be mutually exclusive (i.e., both cannot be correct at the same time) and exhaustive in the context of the case (i.e., one should not consider all propositions as default, but only those that are thought to be of interest to the court). Examples of propositions would be "the DNA mixture is from the defendant and an unrelated person" and "the DNA mixture is from two unrelated persons." Propositions may also be referred to as *hypotheses* or *scenarios*.

R

Random Match Probability (RMP): For single-source DNA profiles, the probability of observing the DNA profile of the Person of Interest (POI) in a random draw from a population or subpopulation group given that the POI's DNA profile has already been observed in the group. Random refers to a hypothetical selection of an individual from the population by any process that is uncorrelated with DNA profiles.

S

Serology: A diagnostic study of biological materials. Serology is synonymous with terms including body fluid identification, biological material examination, and serological screening.

Systems Approach: Examines the relationships between different elements of a system and how they influence the entire system.

T

Technical Leader (TL): An employee who is accountable for the technical operations of the laboratory and who is authorized to initiate, suspend, and resume laboratory operations.

[17] Scientific Working Group on DNA Analysis Methods (SWGDAM). *SWGDAM Guidelines for the Validation of Probabilistic Genotyping Systems*. 2015. https://www.swgdam.org/_files/ugd/4344b0_22776006b67c4a32a5ffc04fe3b56515.pdf.

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Transposing the Conditional (Probability): In general, the phrase refers to exchanging the arguments in a conditional probability so that P(*B*|*A*) becomes P(*A*|*B*). Bayes' rule describes how the transposed probabilities are related to one another; it shows that P(*A*|*B*) involves the prior probability of A as well as the conditional probability P(*B*|*A*). In forensic DNA science, *A* may be a proposition (hypothesis *H*) such as "the defendant is a contributor," and *B* may be the evidence (data *e*) from the DNA testing of the questioned sample and defendant's sample. Equating P(*e*|*H*) with P(*H*|*e*) without considering the prior probability P(*H*) has been called the fallacy of the transposed conditional or the *Prosecutor's Fallacy*.[18]

[18] Semikhodskii A. Chapter 36: Logical Errors and Fallacies in DNA Evidence Interpretation. In: Dash HR, Shrivastava P, Lorente JA, eds. *Handbook of DNA Profiling*. Springer Nature: Singapore, 2022:799-820. ; Thompson WC. Are Juries Competent to Evaluate Statistical Evidence? *Law and Contemporary Problems*. 1989; 52(4):9-41. doi:10.2307/1191906.

1. The Expert Working Group on Human Factors in Forensic DNA Interpretation

The Expert Working Group (EWG) on Human Factors in Forensic DNA Interpretation first convened in February 2020 to conduct a scientific assessment of the effects of human factors on forensic DNA interpretation with the goal of recommending strategies for improving the production, evaluation, and communication of DNA results. A scientific assessment, as defined by the Office of Management and Budget, is "an evaluation of a body of scientific or technical knowledge, which typically synthesizes multiple factual inputs, data, models, assumptions, and/or applies best professional judgment to bridge uncertainties in the available information."[19]

The EWG was charged with:

- Examining human factors as they relate to policies, procedures, and practices within the field of forensic DNA interpretation.
- Developing practices based on scientifically sound research to reduce the likelihood and consequence of errors in forensic DNA interpretation.
- Publishing findings and recommendations to include future research initiatives.

This work was sponsored by the National Institute of Justice (NIJ) Office of Investigative and Forensic Sciences (OIFS) and the National Institute of Standards and Technology (NIST) Special Programs Office.

1.1 EWG Structure and Members

The EWG relied on contributions from many individuals. Members of the EWG were selected by NIST and NIJ staff based on their expertise in the forensic sciences, understanding of human factors principles, background in forensic DNA interpretation practices and training, and understanding of the use of statistics in forensic science and the use of forensic DNA results in the courts. The EWG consisted of an international group of forensic science experts in DNA interpretation (working as sole practitioners or for forensic science service providers [FSSPs]), academics in forensic science and law, statisticians, cognitive scientists, and representatives of professional organizations and standards developing organizations.

The EWG met in-person six times over the course of three and a half years. During the global COVID-19 pandemic, virtual meetings of the full-group or subgroups took place weekly or biweekly.

[19] Office of Management and Budget, Executive Office of the President. Final Information Quality Bulletin for Peer Review. Accessed March 27, 2024. https://www.federalregister.gov/documents/2005/01/14/05-769/final-information-quality-bulletin-for-peer-review. Section I: Definitions.

The EWG subgroups drafted individual chapters and presented drafts to the full EWG. The draft report was developed through a consensus process that allowed each member to comment on and influence all recommendations and text. A panel of independent experts supplied written comments on a completed draft. The Editorial Committee, which consisted of a subset of EWG members, then resolved all comments from the independent experts and presented the final draft to all EWG members for review and final consensus.

The EWG reached substantial agreement on many fundamental issues. The discussion of some topics did not yield a consensus. The report includes information and ideas about these matters that are pertinent to future developments in these areas. Recommendations that did not reach consensus are marked with an asterisk. Dissenting or qualified support statements are presented in corresponding footnotes.

The opinions presented in this report do not represent the official positions of institutions with which members are affiliated.

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We would like to express our gratitude to the following individuals for their contributions as former members of the EWG: **Jocelyn R. Carlson** (DNA Quality Assurance Program Manager, Federal Bureau of Investigation Laboratory), **Matthew M. Farr, MS** (DNA Section Chief, Bureau of Alcohol, Tobacco, Firearms, and Explosives), **Brandon L. Garrett, JD** (L. Neil Williams Professor of Law, Duke University School of Law), **Ashley J. Hinkle, MS** (Crime Lab Scientist, Georgia Bureau of Investigation), **Gabriel Lopez, M Ed.** (Police Commander, Phoenix Police Department), and **Mandi S. Van Buren, MS** (DNA Technical Lead Criminalist, Kern Regional Crime Laboratory). We would also like to express our gratitude to former Steering Committee members **Sarah Norsworthy, MS** (Senior Business Development Analyst, RTI International) and **Donia Slack, MS** (Senior Director, Department of Justice Account, RTI International).

1.2 About the Sponsors

NIJ is the research, development, and evaluation agency of the U.S. Department of Justice and is dedicated to improving knowledge and understanding of crime and justice through science. NIJ provides objective, independent, evidence-based knowledge and tools to inform decision-making of the criminal justice community to advance justice, particularly in state, local, and tribal jurisdictions. NIJ's OIFS is the federal government's lead agency for forensic science research and development as well as the administration of programs and projects that inform federal, state, and local forensic science communities. OIFS forensic science programs and initiatives, through the integration of research and development and technology transition, serve to strengthen the quality and practice of forensic science through research and development, testing and evaluation, technology, and information exchange.

The NIST mission is to advance measurement science, standards, and technology. It accomplishes these actions for the forensic science community through its Special Programs Office's Forensic Science Program (FSP). The FSP directs research efforts to develop performance standards, measurement tools, operating procedures, guidelines, and reports that will advance the field of forensic science. The Special Programs Office also manages the Organization of Scientific Area Committees for Forensic Science (OSAC), which works to strengthen the nation's use of forensic science by facilitating development of technically sound forensic science standards and promoting adoption of those standards by the forensic science community.

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1.3 Acknowledgements

Presenters

The EWG heard presentations from experts in the areas of human factors, cognitive bias, forensic validations, forensic statistics, forensic certification, principles and key competencies of FSSP management and leadership, challenges with presenting DNA evidence in courts, and current and emerging technologies such as probabilistic genotyping software (PGS) for traditional short tandem repeats (STRs) and mixtures. The EWG gratefully acknowledges these individuals for their contributions to the development of this document. The views expressed in this report reflect those of the authors and not necessarily the views of the individuals acknowledged here.

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This report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The reviewers were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. Responsibility for the final content of this report rests entirely with members of the EWG.

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2. Background and Key Concepts

2.1 Introduction and Scope

This chapter outlines the organization of this report, provides the rationale for terminology used, and describes the main process of forensic **DNA analysis** and **DNA interpretation**. Four key concepts that underpin many of the discussions throughout the report are human factors, **systems approach**, **cognitive bias,** and error. Here, the Expert Working Group (EWG) discusses the nature of these topics as they pertain to forensic science.

Specific recommendations for improving DNA evidence interpretation are presented within each chapter. Recommendations should be read in the context of their surrounding material. Some recommendations can be adopted by **forensic science service providers (FSSPs)**, prosecuting authorities, or courts immediately; others may require funding. A few might entail changing the statutes or court rules that apply in different jurisdictions. We believe that all the recommended changes merit serious consideration, and we hope that the surrounding information and analysis will illuminate the issues we have addressed.

Each chapter introduces and defines key terms and acronyms. Terms that appear in bold for their first use are included in the glossary. When FSSPs use multiple terms to refer to a concept, the chapter notes these alternative terms.

Although this report is written specifically within the lens of forensic autosomal short tandem repeat (STR) DNA analysis, much of the content can be applied to other types of DNA analysis (e.g., mitochondrial DNA [mtDNA], Y-chromosome DNA [Y-DNA], Forensic Investigative Genetic Genealogy [FIGG], Rapid DNA) and other forensic disciplines.

2.2 Human Factors and a Systems Approach to DNA Analysis and Interpretation

The study of human factors examines interactions between individuals and all other elements of a system—technology, training, products, procedures, workspaces, the overall environment, resources, institutional culture, and other internal and external factors.[20] Understanding human factors requires understanding the system(s) they operate in. A system is any set of components that work together to produce an outcome. A systems approach examines the relationships between different elements of a system and how they influence the entire system.

Combining a human factors and systems approach, we have reviewed the DNA analysis and interpretation process; the institutional and organizational structures in which DNA analysis is

[20] World Health Organization. *Technical Series on Safer Primary Care: Human Factors*. Geneva. 2016:30. https://www.who.int/publications/i/item/9789241511612.

performed; the wider criminal justice system; and the individuals and groups who produce and use DNA evidence. In doing so, we have developed strategies to enhance the scientific findings in ways that can reduce the possibility of errors and their impact on the criminal justice system. One such strategy involves the role that **DNA analysts** can and should play when explaining the implications of test results to judges and juries. The type of, and limits on, testimony that we describe are intended to permit **DNA experts** to assist, in a scientifically sound and professionally responsible way, the judge or jury in determining the facts of the case.[21]

The EWG comprises forensic scientists, legal practitioners, scholars, statisticians, cognitive scientists, and FSSP managers. These varied perspectives were critical in applying a systems approach.

2.3 A Forensic DNA Analysis Process Map

In 2020, the National Institute of Standards and Technology (NIST) published the Human Forensic DNA Analysis Process Map[22] through a collaboration between the NIST Forensic Science Research Program[23] and the Organization of Scientific Area Committees for Forensic Science (OSAC) Human Forensic Biology Subcommittee, with contributions from the Scientific Working Group on DNA Analysis Methods (SWGDAM).

A **process map** is a workflow diagram of a process or a series of parallel processes. An essential element in identifying opportunities for improvement is examining how a process or current system operates. The Human Forensic DNA Analysis Process Map depicts hundreds of activities and decisions in forensic STR DNA analysis and displays how they are interrelated. This process map is a visual representation of the *current* state of forensic DNA analysis work processes, including inputs, tasks, documentation steps, predefined processes, decision points, outputs, termination/stopping points, and connections among all these elements.

The process map captures the diversity of current practices. It is not a map of best practices or what should be done, but rather a representation of variations of forensic DNA casework

[21] We believe that the expert role we describe is fully compatible with the existing rules of evidence and procedure. See, for example, this reference: (Federal Rule of Evidence. *FRE 702 Testimony by Expert Witnesses*. 2011. https://www.law.cornell.edu/rules/fre/rule_702.) It sets out the basic requirement for all expert testimony that "the expert's scientific, technical, or other specialized knowledge will help the trier of fact to understand the evidence or to determine a fact in issue." See also this reference: (Kaye DH. The Ultimate Opinion Rule and Forensic Science Identification. *Jurimetrics: The Journal of Law, Science, and Technology*. 2020; 60(2):175-85. doi:10.2139/ssrn.3483226.) It explains that the repeal in (Federal Rule of Evidence. *FRE 704 Opinion on an Ultimate Issue*. 2011. https://www.law.cornell.edu/rules/fre/rule_704.) of any categorical rule against opinions on "ultimate issues" does not mandate either source-attribution or inclusion-exclusion testimony. However, we do not suggest that a strength-of-evidence approach is dictated by these rules, and we make no recommendations about the legally permissible bounds of expert testimony.

[22] Organization of Scientific Area Committees (OSAC). *Human Forensic DNA Analysis Process Map*. 2022. https://www.nist.gov/system/files/documents/2022/05/05/OSAC%20Forensic%20Biology%20Process%20Map_5.5.22.pdf.

[23] National Institute of Standards and Technology (NIST). Forensic Science Program. Accessed March 27, 2024. https://www.nist.gov/spo/forensic-science-program.

processes currently performed. We used the process map to understand decision points where there is high variability and increased vulnerability to human factors, such as cognitive bias, to influence the outcomes.

The entire process map spans 42 pages. **Figure 2.1** presents a high-level overview. The main processes include the following:

- **Administrative Assessment** (case intake criteria assessment and capacity assessment)
- **Technical Assessment** (evidence intake)
- **Sample Selection** (case assessment, item characterization, item assessment, and DNA batch planning or triaging)
- **Sample Processing** (extraction, quantitation, amplification, and separation and detection)
- **Genotyping** (generating and assessing the quality of the electropherogram [EPG] and how suitable the profile is for interpretation)
- **Interpretation and Comparison** (number of contributors [NOC] estimation, deconvoluting mixtures [through **binary** or probabilistic approaches], and comparison/statistics)
- **Reporting** (producing a written report and undertaking administrative and technical reviews as well as independent reanalysis)

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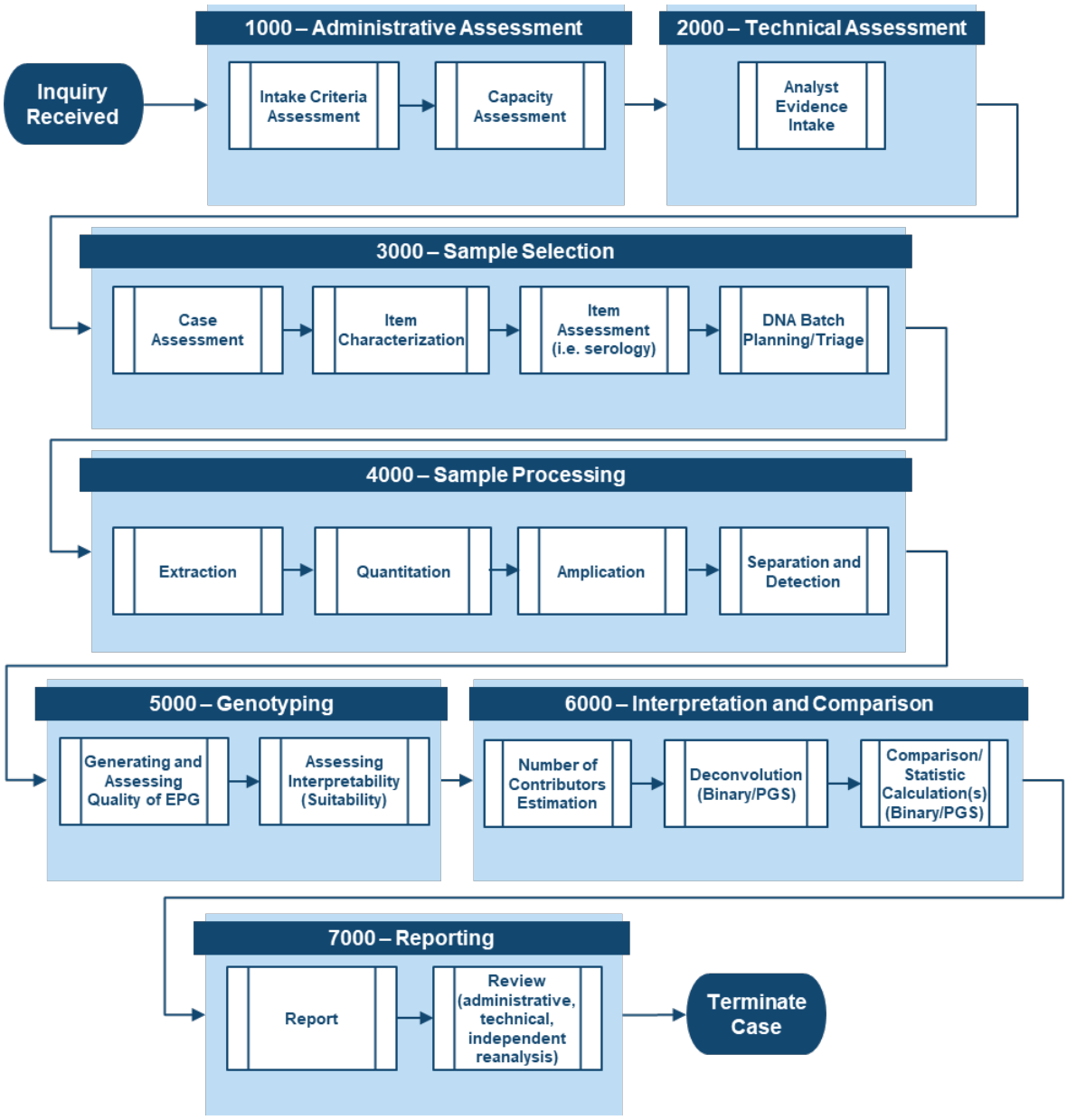

Figure 2.1: Overview of the human forensic DNA analysis process map.

Readers can access the map[24] in conjunction with this report or, more broadly, for additional information on workflow and decision-making in STR profiling. This report is not confined to the processes within this map; it also explores processes that occur before the assessment of intake criteria and those that follow reporting.

[24] Organization of Scientific Area Committees (OSAC). *Human Forensic DNA Analysis Process Map*. 2022. https://www.nist.gov/system/files/documents/2022/05/05/OSAC%20Forensic%20Biology%20Process%20Map_5.5.22.pdf.

2.4 Cognitive Bias

As long as a human analyzes and interprets forensic DNA evidence, the strengths and limitations of human cognition will be central to forensic casework. With human cognition, there is always a chance that expectations, task-irrelevant information, and preexisting prejudices can affect decision-making.

There are many forms of cognitive bias. A recent, sweeping definition equates cognitive bias to "effects by which an individual's preexisting beliefs, expectations, motives, and situational context may influence their collection, perception, or interpretation of information, or their resulting judgments, decisions, or confidence." [25] Cognitive bias can result from cognitive shortcuts (sometimes called **heuristics**) which help to make sense of the world quickly and efficiently. Biases do not necessarily produce error, but they can tilt judgments or measurements in one direction.

Two types of cognitive bias are generally applicable to DNA analysis—**confirmation bias** and **contextual bias**. Confirmation bias is present when preexisting beliefs and expectations lead individuals to give weight and attention to information that confirms their preexisting beliefs and less weight and attention to information that disconfirms their beliefs. [26] Contextual bias describes "human judgement being influenced by irrelevant contextual information." [27] These and other types of cognitive bias are discussed throughout the report.

Criminal justice partners[28] receiving DNA analysts' opinions are also subject to cognitive bias. The expectations these groups of individuals have about a case or a type of evidence may frame their perception of the evidence. For instance, **factfinders**[29] (i.e., judge or jurors) may bring with them assumptions that DNA evidence is infallible.[30] They might misunderstand the qualifications, style, wording, or visual presentation of findings in a report, or they may misinterpret

[25] Spellman BA, Eldridge H, Bieber P. Challenges to Reasoning in Forensic Science Decisions. *Forensic Science International: Synergy*. 2022; 4:100200. doi:10.1016/j.fsisyn.2021.100200.

[26] Nickerson RS. Confirmation Bias: A Ubiquitous Phenomenon in Many Guises. *Review of General Psychology*. 1998; 2(2):175-220. doi:10.1037/1089-2680.2.2.175.

[27] Expert Working Group for Human Factors in Handwriting Examination. Forensic Handwriting Examination and Human Factors: Improving the Practice through a Systems Approach. NIST IR 8282r1. National Institute of Standards and Technology; 2021. doi:10.6028/NIST.IR.8282r1

[28] "Criminal justice partner" is synonymous with "stakeholder," but the latter has been said to be stigmatizing; Centers for Disease Control and Prevention. Preferred Terms for Select Population Groups & Communities. Accessed March 26, 2024. https://www.cdc.gov/healthcommunication/Preferred_Terms.html; Sharfstein JM. Banishing "Stakeholders". *The Milbank Quarterly*. 2016; 94(3):476-9. doi:10.1111/1468-0009.12208.

[29] Term used to describe the impartial individual(s) who have been tasked with appraising the facts that underlie a particular matter (e.g., the ultimate question[s]) in a case. The judge or jury is the factfinder in criminal trials.

[30] Martire KA, Ballantyne KN, Bali A, Edmond G, Kemp RI, Found B. Forensic Science Evidence: Naive Estimates of False Positive Error Rates and Reliability. *Forensic Science International*. 2019; 302:109877. doi:10.1016/j.forsciint.2019.109877; Ribeiro G, Tangen JM, McKimmie BM. Beliefs About Error Rates and Human Judgment in Forensic Science. *Forensic Science International*. 2019; 297:138-47. doi:10.1016/j.forsciint.2019.01.034.

probabilistic and statistical statements.[31] ***Chapter 6: Pre-Trial Preparation and Testimony*** discusses these topics.

2.4.1 Cognitive Bias and Forensic DNA Interpretation

Some sources of information that a DNA analyst[32] encounters during an examination will affect the decision-making process more than others. Dror[33] has enumerated eight sources of bias that range from broad human nature considerations to case and evidence-specific considerations (see **Fig. 2.2**). It is important to note that not all information is biasing and that it can be difficult, a priori, to classify information as relevant or irrelevant and biasing or non-biasing.

Tasks requiring more cognitive effort are generally more susceptible to bias.[34] Greater cognitive effort is required when results are complex and data are ambiguous, when there are time pressures, when a large amount of information must be combined and processed, or when decisions are discretionary (see ***Sec. 3.3.1: Discretionary Decisions Versus Standard Operating Procedures***). These conditions do not always cause bias or generate an inaccurate decision, but they increase the risk that decisions will be affected by irrelevant or contaminating information.

[31] Kilberger KB. Something Doesn't Add Up: Solving DNA Forensic Science Statistical Fallacies in Trial Testimony. *Vanderbilt Journal of Entertainment and Technology Law*. 2023; 25(1):181-209. ; Martire KA. Clear Communication through Clear Purpose: Understanding Statistical Statements Made by Forensic Scientists. *Australian Journal of Forensic Sciences*. 2018; 50(6):619-27. doi:10.1080/00450618.2018.1439101; Murphy E, Thompson WC. Common Errors and Fallacies in Forensic DNA Statistics: An Amicus Brief in McDaniel v. Brown. *Criminal Law Bulletin*. 2010; 46:709. ; Saks MJ, Koehler JJ. The Individualization Fallacy in Forensic Science Evidence. *Vanderbilt Law Review*. 2008;61:199-219. Accessed March 27, 2024. https://scholarship.law.vanderbilt.edu/vlr/vol61/iss1/4; Thompson WC, Schumann EL. Interpretation of Statistical Evidence in Criminal Trials: The Prosecutor's Fallacy and the Defense Attorney's Fallacy. *Law and Human Behavior*. 1987; 11(3):167-87. doi:10.1007/bf01044641.

[32] An individual who has completed training requirements for casework sample analysis, passed a competency test, and is subject to a proficiency testing program. This individual can conduct or direct the analysis of forensic samples, interpret data, reach conclusions, and generate reports. This definition includes both individuals who process the DNA samples and those who perform the statistical analysis and interpretation of the DNA results (for FSSPs who separate these functions).

[33] Dror IE. Cognitive and Human Factors in Expert Decision Making: Six Fallacies and the Eight Sources of Bias. *Analytical Chemistry*. 2020; 92(12):7998-8004. doi:10.1021/acs.analchem.0c00704.

[34] Dror IE, Péron AE, Hind S-L, Charlton D. When Emotions Get the Better of Us: The Effect of Contextual Top-Down Processing on Matching Fingerprints. *Applied Cognitive Psychology*. 2005; 19(6):799-809. doi:10.1002/acp.1130; Nickerson RS. Confirmation Bias: A Ubiquitous Phenomenon in Many Guises. *Review of General Psychology*. 1998; 2(2):175-220. doi:10.1037/1089-2680.2.2.175; Osborne NKP, Zajac R. An Imperfect Match? Crime‐Related Context Influences Fingerprint Decisions. *Applied Cognitive Psychology*. 2015; 30(1):126-34. doi:10.1002/acp.3180; Taylor MC, Laber TL, Kish PE, Owens G, Osborne NKP. The Reliability of Pattern Classification in Bloodstain Pattern Analysis, Part 1: Bloodstain Patterns on Rigid Non-Absorbent Surfaces. *Journal of Forensic Sciences*. 2016; 61(4):922-7. doi:10.1111/1556-4029.13091.

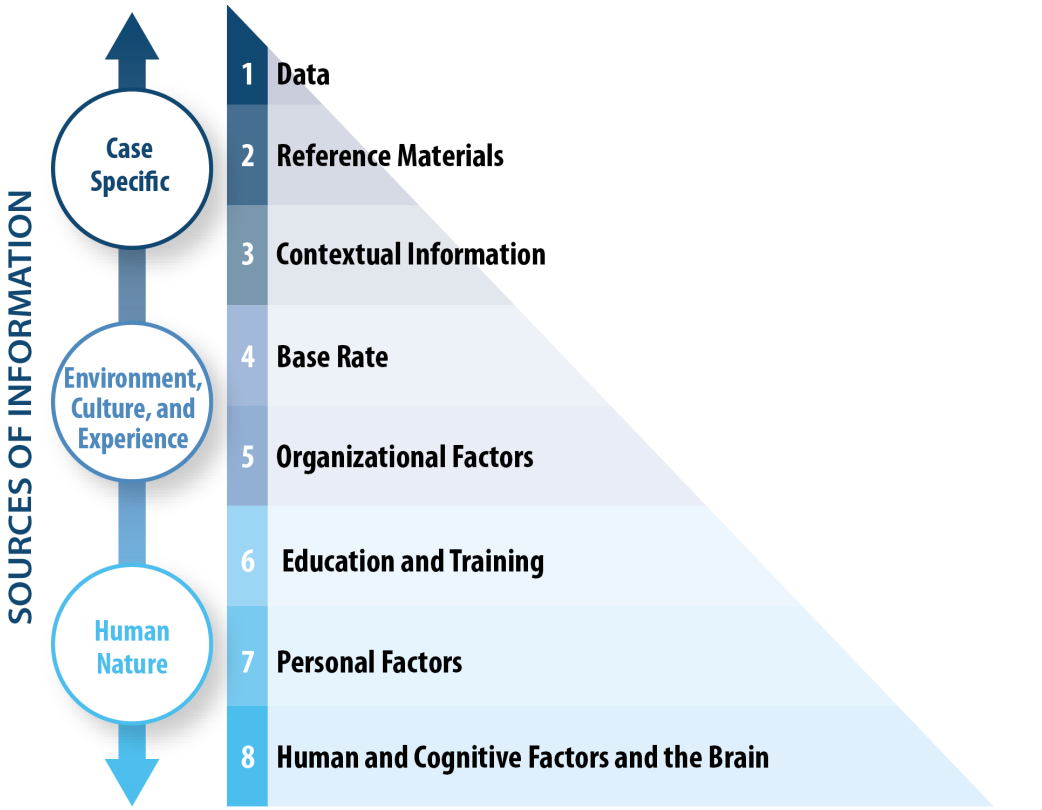

Figure 2.2. Eight sources of information that may cognitively contaminate a forensic examination.

Figure originally appeared in Dror, 2020 and adapted with permission.[35]

Although there are many studies of bias across forensic science disciplines[36] and several interlaboratory studies of the variability of interpretations of mixed DNA samples,[37] only a single study has examined the impact of contextual information on the interpretation of DNA mixtures. Dror and Hampikian[38] examined variability in DNA mixture interpretation decisions between DNA analysts in a Georgia case who had contextual information and 17 other North American

[35] Dror IE. Cognitive and Human Factors in Expert Decision Making: Six Fallacies and the Eight Sources of Bias. *Analytical Chemistry*. 2020; 92(12):7998-8004. doi:10.1021/acs.analchem.0c00704.

[36] For review, see Cooper GS, Meterko V. Cognitive Bias Research in Forensic Science: A Systematic Review. *Forensic Science International*. 2019; 297:35-46. doi:10.1016/j.forsciint.2019.01.016.

[37] Brinkac LM, Richetelli N, Davoren JM, Bever RA, Hicklin RA. DNAmix 2021: Laboratory Policies, Procedures, and Casework Scenarios Summary and Dataset. *Data Brief*. 2023; 48:109150. doi:10.1016/j.dib.2023.109150; Buckleton J, Bright JA, Cheng K, Budowle B, Coble MD. NIST Interlaboratory Studies Involving DNA Mixtures (MIX13): A Modern Analysis. *Forensic Science International: Genetics*. 2018; 37:172-179. doi:10.1016/j.fsigen.2018.08.014; Butler JM, Kline MC. NIST Mixture Interpretation Interlaboratory Study 2005 (MIX05). Presented at: Promega 16th International Symposium on Human Identification 2005; Grapevine, TX. https://strbase-archive.nist.gov/interlab/MIX05/MIX05poster.pdf ; Butler JM, Kline MC, Coble MD. NIST Interlaboratory Studies Involving DNA Mixtures (MIX05 and MIX13): Variation Observed and Lessons Learned. *Forensic Science International: Genetics*. 2018; 37:81-94. doi:10.1016/j.fsigen.2018.07.024; Hicklin RA, Richetelli N, Emerick BL, Bever RA, Davoren JM. Variation in Assessments of Suitability and Number of Contributors for DNA Mixtures. *Forensic Science International: Genetics*. 2023; 65:102892. doi:10.1016/j.fsigen.2023.102892.

[38] Dror IE, Hampikian G. Subjectivity and Bias in Forensic DNA Mixture Interpretation. *Science & Justice*. 2011; 51(4):204-8. doi:10.1016/j.scijus.2011.08.004.

DNA analysts who did not.[39] They observed variability both between the context and context-free interpretation conditions and within the context-free condition. There are several methodological limitations with this study,[40] and the authors guardedly concluded that "for those who were exposed to the extraneous [information], it is possible that the domain irrelevant information may have biased their interpretation."[41]

Given the robust findings of the susceptibility of human decisionmakers to biasing information in so many domains and in other forensic science disciplines, it seems clear that DNA analysts are not immune to bias. ***Sec. 3.3.4: Contextual Information Management*** provides further discussion and examples related to bias mitigation strategies in forensic DNA analysis.

2.5 Error

Error occurs in all human endeavors. Employing a systems approach to understanding and identifying errors involves looking at the entire process of forensic DNA analysis as a complex system, rather than focusing solely on individual factors in isolation. Sample collection, preservation, analysis, and interpretation as well as organizational and institutional factors influence the process. This section provides a brief overview of the various ways in which errors can be understood. Later chapters examine errors in the context of each chapter's topic.

Chapter 8: Quality Assurance/Quality Control (QA/QC) discusses specific ways that FSSPs can prevent or mitigate laboratory errors. ***Chapter 10: Management*** discusses FSSP management and leadership's role in providing support to prevent and correct errors. FSSPs should also work toward an honest and transparent system of accountability for errors that are discovered at any time in the process, including post-conviction, to ensure constant improvement of the system and the fair and just use of forensic science in the criminal justice system. ***Chapter 6: Pre-Trial Preparation and Testimony*** discusses discovery and disclosure obligations specifically related to trial and testimony.

[39] The potentially biasing information was that the prosecutor needed a DNA association with a particular suspect in a gang-rape case to proceed to trial. The article does not state how the analysts learned that the suspect could not be charged unless they concluded that he was associated with the rape through the DNA evidence. It does not state how many analysts worked on the case and whether their conclusions were arrived at independently, or instead whether each analyst was exposed to the conclusion of other analysts before forming an opinion.

[40] The Dror (2011) article does not state whether the two laboratories had the same protocols and whether the DNA analysts in the context-free condition worked independently on the exercise. For discussion of the extent to which the study justifies inferences on the possible causes of the differences in the results from the two sets of examiners, see Dror IE. Cognitive Forensics and Experimental Research About Bias in Forensic Casework. *Science & Justice*. 2012; 52(2):128-30. doi:10.1016/j.scijus.2012.03.006; Kaye DH. The Design of "The First Experimental Study Exploring DNA Interpretation". *Science & Justice*. 2012; 52(2):126-7; author reply 128-30. doi:10.1016/j.scijus.2011.10.003.

[41] Dror IE, Hampikian G. Subjectivity and Bias in Forensic DNA Mixture Interpretation. *Science & Justice*. 2011; 51(4):204-8. doi:10.1016/j.scijus.2011.08.004. p. 205.

2.5.1 Defining Error from a Human Factors Perspective

Error is often discussed in forensic science, yet it is admittedly difficult to find a single, unifying definition for the criminal justice system. In statistics, error is the difference between a true value and a measured or estimated value. But it can also be defined as "the act or an instance of deviating from an accepted code of behavior."[42] Likewise, legal errors can occur when procedural rules are not followed—even if the factfinder's determination is factually accurate. Error may also be described as a mistake, slip, lapse, violation, nonconformity, suboptimal outcome, or discrepancy.

We define error as the failure of a system to achieve its intended goal or outcome. This broad definition recognizes that errors can result from a complex interaction of factors, including individual actions, organizational processes, and environmental conditions. Errors can occur at any point in a system. To address error adequately, the entire system must be analyzed to identify the causes of errors, including issues related to communication, training, design, cognitive bias, and organizational culture.

No approach to error can be expected to eliminate all errors, at all times, with all people, and with all equipment. Instead, the goal is to minimize the risk of errors and to create a system that is resilient and transparent in the face of errors. To achieve this goal, FSSPs should design flexible and adaptable systems that promote communication and collaboration. When identified, FSSPs should treat errors as valuable opportunities for learning and improvement (see ***Sec. 10.6: Shaping FSSP Culture***).

In short, FSSPs and DNA analysts must be aware of the actions and conditions that could lead to errors and take steps to improve these conditions to minimize the occurrence of errors. Such steps could include implementing stronger quality control measures, adhering to established standards and protocols, and engaging in ongoing training and education (see ***Sec. 8.10: Nonconformity Detection and Prevention***). Of paramount importance, FSSPs should take a systems approach to error reduction rather than regarding errors as isolated acts of individuals that automatically result in punitive measures (see ***Sec. 10.6.4: Non-Punitive Error Culture***).

2.5.2 Defining Error from a Forensic Science Perspective

The criminal justice system relies on forensic science results and opinions. Criminal justice partners expect that the information a DNA expert supplies is accurate and reliable. Yet, errors

[42] Christensen AM, Crowder CM, Ousley SD, Houck MM. Error and Its Meaning in Forensic Science. *Journal of Forensic Sciences*. 2014; 59(1):123-6. doi:10.1111/1556-4029.12275. p. 123.

can occur in any step prior to a reported opinion (**process error**) and in the final opinion (**outcome error**).[43]

The following is a non-exhaustive list of process errors that might lead to an outcome error:

- Contamination
- Mislabeling samples
- Incorrect chain of custody
- Failing to collect or test a sample
- Poorly calibrated instruments
- Incorrect assessment or assignment of NOC
- Clerical mistakes
- Sample switch
- Setting inappropriate **propositions**
- Inappropriate use or application of methods
- Denying all possibility of error
- Failing to follow standard operating procedures
- Misinterpreting artifacts
- Misuse of software
- Miscalculation of statistics
- Using unvalidated methods or software
- Omitting relevant data from the analysis
- Not conveying the limitations and caveats of the results

These actions could be the result of many causes, including inadequate training, poor judgment, stress, insufficient resources, FSSP culture, or ineffective management or quality control measures.

2.5.3 Error Rates

Error rates provide information on performance to courts and factfinders (see ***Sec. 6.6: Pre-Trial Admissibility Hearings***).[44] Calculating an error rate for DNA analysis, however, is problematic for several reasons.[45] Error rates in casework are difficult to estimate because there is no ground truth to compare the DNA results to. Although "black box" and "white box" studies go some way in elucidating reliability and validity, estimates will be impacted by how the researchers define error, who the participants are, and how "inconclusive" or non-responses are counted.[46] Furthermore, ground-truth-known materials developed to measure accuracy may not reflect casework, and the experimental conditions under which individuals analyze the material are generally designed to test individuals and not the system. Indeed, it has been suggested that black box–produced error rates in forensic science are likely to underestimate true rates of error

[43] Expert Working Group on Human Factors in Latent Print Analysis. Latent Print Examination and Human Factors: Improving the Practice through a Systems Approach. National Institute of Standards and Technology; 2012. doi:10.6028/NIST.IR.7842

[44] United States Supreme Court. *Daubert v. Merrell Dow Pharmaceuticals (92-102), 509 U.S. 579*. 1993.

[45] Dror IE. Commentary On: The Error in "Error Rate": Why Error Rates Are So Needed, Yet So Elusive. *Journal of Forensic Sciences*. 2020; 65(4):1034-9. doi:10.1111/1556-4029.14435.

[46] Khan K, Carriquiry AL. Shining a Light on Forensic Black-Box Studies. *Statistics and Public Policy*. 2023; 10(1):2216748. doi:10.1080/2330443x.2023.2216748.

in casework.[47] The use of **likelihood ratios** (LRs) rather than match/no-match conclusions further complicates error rate calculations (see ***Sec. 4.3*: *The Likelihood Ratio***).

The 2016 President's Council of Advisors on Science and Technology (PCAST) Report [48] recommends that subjective feature-comparison methods such as fingerprint or firearms comparisons be accompanied by error rates that enable judges and juries to assign **probative value** appropriately.[49] Although the PCAST report stated that "errors can and do occur in DNA testing" and that the chance of human error is higher than that of an adventitious match,[50] the report made no recommendation regarding if and how to consider the possibility of error in DNA interpretation.

In 2014, the Netherlands Forensic Institute (NFI) reported the rate of quality issues found in their DNA laboratory's casework.[51] They presented the observed number of quality issues divided by the total number of DNA analyses, as the proportion of cases in which an error occurred. They defined quality issues to encompass contamination, human error, technical problems, deviation from quality documents, capacity/planning errors, deviation from the FSSP's competence matrix, and sample mix-up. Human error and contamination were the most common quality issues.[52] Reporting "errors" in this way allows for feedback, transparency, and improved quality processes, but the reported rates do not correspond to the probability that an error occurred in a particular case.

From a legal perspective, when presenting results, the possibility of error should not be ignored. The risk should either be incorporated into the analyst's evaluation or acknowledged separately. Factfinders should never be given the impression that DNA opinions have a zero-error rate.

2.6 The Duty to Correct or Report Errors and Adverse Events

Errors and adverse events[53] will differ in their severity and potential to negatively impact the judicial process. Just as it is not the FSSP's or DNA analyst's role to determine guilt or innocence or make legal judgments concerning discovery or disclosure obligations, it is also not their role to determine whether a miscarriage of justice has occurred. However, withholding or failing to

[47] Ibid.

[48] President's Council of Advisors on Science and Technology (PCAST). *Report to the President: Forensic Science in Criminal Courts: Ensuring Scientific Validity of Feature-Comparison Methods*. 2016. https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/PCAST/pcast_forensic_science_report_final.pdf.

[49] Ibid.

[50] Ibid.

[51] Kloosterman A, Sjerps M, Quak A. Error Rates in Forensic DNA Analysis: Definition, Numbers, Impact and Communication. *Forensic Science International: Genetics*. 2014; 12:77-85. doi:10.1016/j.fsigen.2014.04.014.

[52] Ibid.

[53] Adverse events might include good faith or malfeasant behavior; see National Commission on Forensic Science. *Recommendation to the Attorney General: Root Cause Analysis (RCA) in Forensic Science*. 2015. https://www.justice.gov/archives/ncfs/file/786581/download.

correct material information could compromise the integrity of the analyst, the FSSP, and the criminal justice system.

DNA analysts and FSSPs have an ethical and professional duty to correct significant errors.[54] If an analyst, reviewer, or other FSSP personnel discovers that information in a report or testimony is likely to be incorrect, based on unsound or misapplied science, or the result of incompetent practice or nefarious behavior, then the FSSP personnel should report the matter to FSSP management. FSSP management should first determine whether a nonconformity or other egregious action has taken place. Ordinarily, an analyst's report to management will result in appropriate corrective action by management, but there can be instances in which an analyst may believe that management has not adequately addressed a serious problem (see ***Sec. 8.10.2: Corrective Actions***). In these instances, the analyst may need to seek support or guidance from professional societies or outside counsel on how to proceed.

Obligations regarding errors and adverse events may vary depending on the nature of the error[55] and the time at which it is discovered. Appropriate responses may overlap with some criminal justice partners' obligations of disclosure or notification and require guidance and involvement of those participants. The EWG references the phrase "duty to correct" broadly but understands these nuances. The discussion is intended to prompt FSSP management and personnel and lawyers involved in the criminal justice system to discover and address errors at all applicable stages.

FSSPs should define the criteria for determining if a nonconformity[56] or other adverse event has taken place prior to making assessments regarding these incidents to ensure consistent and fair assessment. These criteria also need to consider an assessment of risk (see ***Sec. 8.10.1: Risk Analysis***). Although the FSSP should institute a structure for such assessments, judgments as to legal relevance and materiality must also involve communications with and guidance from other participants in the criminal justice system.

[54] Chu S. Duty to Correct and Notify. In: Houck MM, ed. *Encyclopedia of Forensic Sciences*. 3rd ed. Elsevier: Oxford, 2023:186-92. doi:10.1016/B978-0-12-823677-2.00172-0.

[55] A mistake or slip may be simple to correct and not require any reporting outside of the FSSP and should not be treated the same as misconduct or negligence.

[56] Nonconformities are defined in the Department of Justice Code of Professional Responsibility for the Practice of Forensic Science (the Code) as any "aspect of laboratory work that does not conform to its established procedures. An evaluation of the non-conformity risk is appropriate to deciding whether or not reporting is necessary." United States Department of Justice. *Code of Professional Responsibility for the Practice of Forensic Science* 2016. https://www.justice.gov/sites/default/files/code_of_professional_responsibility_for-the_practice_of_forensic_science_08242016.pdf.

In addition, FSSPs should consider accrediting and oversight bodies' standards, guidelines, and requirements in evaluating and responding to potential errors.[57] Based on internal, predefined guidelines, FSSP management should determine if the findings need to be disclosed to criminal justice partners or accrediting bodies. For example, the Department of Justice's *Code of Professional Responsibility for the Practice of Forensic Science* states that FSSP management must "[i]nform the prosecutors involved through proper laboratory management channels of material nonconformities or breaches of law or professional standards that adversely affect a previously issued report or testimony."[58] Appropriate actions may depend on the jurisdiction where the DNA expert testified, who the report was prepared for, and the policy of the FSSP or oversight body. FSSPs should have a policy defining who should be notified and how.[59]

FSSPs, certifying bodies, and professional societies should incorporate a duty to correct into their code of conduct. This should include a written policy that outlines, at a minimum, when there is a duty for the FSSP or DNA analyst to notify of an error or an adverse event and who should be notified.

Bad faith, incompetence, and malfeasance are not required to trigger the need for a correction. Indeed, the duty to correct may apply to methods that were fully aligned with an FSSP's protocols, relevant laws, and professional standards at the time a report was issued. The appropriateness and value of those reports and testimony could shift as the science or the parties' understanding of legal requirements evolves.

[57] ANSI National Accreditation Board (ANAB). *Accreditation Manual for Forensic Laboratories, Forensic Inspection Bodies, and Property and Evidence Control Units*. 2024. https://anab.qualtraxcloud.com/ShowDocument.aspx?ID=7183; ANSI National Accreditation Board (ANAB). *AR 3125: Accreditation Requirements for Forensic Testing and Calibration (2023)*. 2023. https://anab.qualtraxcloud.com/ShowDocument.aspx?ID=12371.

[58] United States Department of Justice. *Code of Professional Responsibility for the Practice of Forensic Science* 2016. https://www.justice.gov/sites/default/files/code_of_professional_responsibility_for-the_practice_of_forensic_science_08242016.pdf.

[59] Texas Administrative Code: 37. *§651.216. Disciplinary Action*. 2018. https://texreg.sos.state.tx.us/public/readtac$ext.TacPage?sl=T&app=9&p_dir=P&p_rloc=196522&p_tloc=&p_ploc=1&pg=7&p_tac=&ti=37&pt=15&ch=651&rl=216

3. Interpretation

3.1 Introduction and Scope

Forensic science service provider (FSSP) work is a complex system of interconnected steps, where the outcome of each step can influence later decisions or outcomes. Within each of these steps, human factors can play a role in the interpretation of forensic results. For example, whether a peak in an electropherogram (EPG) is categorized as an artifact may influence the assignment of the number of contributors (NOC), which may further influence whether the DNA analyst determines if the profile is suitable for comparison. Similarly, the value of the item may vary depending on the assumptions made by the DNA analyst (e.g., assuming or conditioning on the presence of a known contributor). In these examples, there is a point in the process where the DNA analyst acquires and integrates information for the purpose of deciding how to proceed.[60]

This chapter begins by reviewing general human factors issues that should be considered once the FSSP receives the item and throughout DNA analysis.[61] This chapter then addresses human factors according to specific interpretation tasks or decisions that the DNA analyst may need to make throughout the course of an analysis, including:

- selecting items to test and examine;
- determining the locations for testing or collection of an item;
- producing profiles and determining suitability for analysis;
- determining the purpose of analyses;
- making comparisons to **Person of Interest (POI)**[62] profiles;
- deciding to upload a DNA profile to a DNA database; and
- assessing when or if reanalysis is necessary.

While decisions influencing *how* the data are interpreted are important, *what* data are interpreted can be as influential. For that reason, we not only consider the points at which human factors can influence interpretation, but also how human factors impact the data generating process itself.

[60] Organization of Scientific Area Committees (OSAC). *Human Forensic DNA Analysis Process Map*. 2022. https://www.nist.gov/system/files/documents/2022/05/05/OSAC%20Forensic%20Biology%20Process%20Map_5.5.22.pdf.

[61] There are many decisions that may be made prior to an item being received by the FSSP that may impact the results obtained (e.g., what evidence is collected and the manner of collection). These are not discussed in this report, as they are true for all forensic disciplines.

[62] POI is not synonymous with suspect. A POI can extend to any individual, including those needing to be compared for elimination purposes.

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The role of technology is central to many of these discussions. A significant portion of this chapter concerns using probabilistic genotyping software (PGS) to assist with the interpretation of complex DNA profiles.

This chapter is closely linked to ***Chapter 4: Quantitative and Qualitive Ways to Express DNA Results***, which elaborates on the value or meaning of the **DNA results** and how those results can or should be expressed. It is also closely related to ***Chapter 5: Reporting*** and ***Chapter 6: Pre-Trial Preparation and Testimony*** since these chapters address communicating the results, testifying to expert opinions, and how factfinders and other interested parties understand these communications. A discussion of interpretation as it pertains to **serology** screening is presented in ***Sec. 4.6: Interpretation and Expression of Serological Screening Results***.

3.2 Basic Overview of DNA Interpretation Phases

The primary focus of this chapter is interpretation considerations when questions relate to the *source* of the DNA. The question presented to the analyst may be, "Could the DNA have originated from this POI?" or "Is the DNA associated with a convicted offender, an arrestee, or an unidentified profile from another incident in a DNA database?" Broadly, interpretation involves four phases: ***case management***, *pre-comparison*, *comparison*, and *post-comparison*. These phases are discussed separately although, in practice, they often happen concurrently.[63]

3.2.1 Case Management

Case management relates to the assessment, prioritization, and assignment of cases for examination. It also extends to monitoring testing and the turnaround time needed to complete the requested tasks. **Contextual information management (CIM)** is a part of case management that seeks to minimize analysts' exposure to task-irrelevant information while ensuring that all task-relevant information is available to the analyst (see ***Sec. 3.3.4: Contextual Information Management***).[64]

During case assessment, the relevant investigative questions and case items should be evaluated to establish if DNA analysis can be useful. Investigative questions of interest are not always immediately clear, and changes in investigative information can impact assessments. Therefore,

[63] Although not covered here, human factors also influence steps prior to the case management phase, such as collecting items as part of the criminal investigation and submitting them to the FSSP for testing.

[64] Jeanguenat AM, Budowle B, Dror IE. Strengthening Forensic DNA Decision Making through a Better Understanding of the Influence of Cognitive Bias. *Science & Justice*. 2017; 57(6):415-20. doi:10.1016/j.scijus.2017.07.005; Mattijssen EJ, Kerkhoff W, Berger CEH, Dror IE, Stoel RD. Implementing Context Information Management in Forensic Casework: Minimizing Contextual Bias in Firearms Examination. *Science & Justice*. 2016; 56(2):113-22. doi:10.1016/j.scijus.2015.11.004; Osborne NKP, Taylor MC. Contextual Information Management: An Example of Independent-Checking in the Review of Laboratory-Based Bloodstain Pattern Analysis. *Science & Justice*. 2018; 58(3):226-31. doi:10.1016/j.scijus.2018.01.001; Quigley-McBride A, Dror IE, Roy T, Garrett BL, Kukucka J. A Practical Tool for Information Management in Forensic Decisions: Using Linear Sequential Unmasking-Expanded (LSU-E) in Casework. *Forensic Science International: Synergy*. 2022; 4:100216. doi:10.1016/j.fsisyn.2022.100216.

effective and timely communication between the investigative agency and the FSSP case manager becomes essential. If this step is mishandled, the appropriate examination may not occur.

3.2.1.1 The Importance of Case Assessment and Information

Determining if DNA testing can help answer the questions posed is a critical decision point. An investigation may start with the question of "Whose DNA was left at the scene?" but as more information is obtained, the question may become "How was the DNA left at the scene?" In other instances, the source of the DNA or parties involved may not be in question, and DNA testing to help address source-level questions may not be of value. Investigators may be interested in other questions. For example:

- What type of biological material is present (or absent)? (See ***Sec. 4.6: Interpretation and Expression of Serological Screening Results***)
- Is male (or female) DNA present? (See ***Sec. 5.3.2.3: Distinguishing Between Male and Female DNA***)
- Is the DNA profile associated with any profiles in a DNA database? (See ***Sec. 5.3.2.2: Investigative Leads Produced Following DNA Database Searches***)
- Could the DNA have originated from a POI? (See ***Sec. 5.3.1: Reporting When There is a POI Profile for Comparison***)
- Are there possible alternate explanations for the results? (See ***Sec. 5.3.2.4: Possible Explanations for DNA Results***)
- How and when was the DNA deposited? (See ***Chapter 7: How and When Questions in DNA Analysis***)

Case assessment is the stage at which the FSSP determines what items to test and why. Access to relevant case information is critical for this purpose, even if that information is potentially biasing. For CIM purposes, the FSSP needs to consider who has access to this case information and when (see ***Sec. 3.3.4: Contextual Information Management***).

Regardless of the interpretation method employed, it is important that the DNA analyst follows the principles of interpretation[65] (see ***Sec. 3.5: Comparison Phase***). That is, the interpretation should: (1) consider the task-relevant case information; (2) be balanced and consider two

[65] European Network of Forensic Science Institutes (ENFSI). *ENFSI Guideline for Evaluative Reporting in Forensic Science: Strengthening the Evaluation of Forensic Results across Europe (STEOFRAE), Version 3.0*. 2015. https://enfsi.eu/wp-content/uploads/2016/09/m1_guideline.pdf; Evett IW, Jackson G, Lambert JA, McCrossan S. The Impact of the Principles of Evidence Interpretation on the Structure and Content of Statements. *Science & Justice*. 2000; 40(4):233-9. doi:10.1016/S1355-0306(00)71993-9; Evett IW, Weir BS. *Interpreting DNA Evidence: Statistical Genetics for Forensic Scientists*. Sinauer Associates Inc,: Sunderland, MA, 1998. ; Hicks T, Buckleton J, Castella V, Evett IW, Jackson G. A Logical Framework for Forensic DNA Interpretation. *Genes (Basel)*. 2022; 13(6):957. doi:10.3390/genes13060957; Jackson G. The Scientist and the Scales of Justice. *Science & Justice*. 2000; 40(2):81-5. doi:10.1016/S1355-0306(00)71947-2; Jackson G, Jones S, Booth G, Champod C, Evett IW. The Nature of Forensic Science Opinion - a Possible Framework to Guide Thinking and Practice in Investigations and in Court Proceedings. *Science & Justice*. 2006; 46(1):33-44. doi:10.1016/s1355-0306(06)71565-9.

opposing views or propositions; and (3) be conveyed in the form of statements about the DNA results and not opinions of what happened.

The FSSP or DNA analyst should also capture the investigative questions in the propositions they consider. Propositions are sometimes called hypotheses or scenarios. A framework called the **hierarchy of propositions** can help analysts formulate propositions that are appropriate for the issue(s) at hand (see **Table 3.1**).[66] In general, there are three levels of this hierarchy: source, activity, and offense. Source-level issues can be broken down further into sub-source and sub-sub-source issues.

The analyst can help address—but should not directly answer—questions about whether a given individual is the source of the biological material or not. As explained in ***Chapter 7: How and When Questions in DNA Analysis***, what can or should be said about how and when DNA was deposited is a topic of ongoing scientific and legal discussion. Offense-level issues are exclusively in the purview of the factfinder and are not discussed in this report.

Table 3.1: Examples of pairs of mutually exclusive propositions at the source and activity levels of the hierarchy of propositions

Level	Question/Issue	Results	Example of Pairs of Propositions
Activity	Did the POI perform the activity?	• Presence/absence of DNA at different locations • Quantity/quality of the DNA (DNA profiling comparison) • Presumptive tests • Multiple traces from the same activity	• Mr. A and Ms. B had penile-vaginal intercourse. • Mr. A and Ms. B only partook in social activities as described in the case information.
			• Mr. Smith was the driver, and Mr. Jones was the passenger at the relevant time. • Mr. Jones was the driver, and Mr. Smith was the passenger at the relevant time.
Source	Is the POI the source of the biological material?	• DNA profiling comparison	• Mr. A is the source of the blood. • An unknown individual is the source of the blood.
Sub-Source	Is the POI the source of the DNA?		• Mr. A is the source of the DNA. • An unknown individual is the source of the DNA.
Sub-Sub-Source	Is the POI the source of part of the mixture?		• Mr. A is the major contributor of the DNA mixture.

[66] Cook R, Evett IW, Jackson G, Jones PJ, Lambert JA. A Hierarchy of Propositions: Deciding Which Level to Address in Casework. *Science & Justice*. 1998; 38(4):231-9. doi:10.1016/S1355-0306(98)72117-3; Hicks T, Buckleton J, Castella V, Evett IW, Jackson G. A Logical Framework for Forensic DNA Interpretation. *Genes (Basel)*. 2022; 13(6):957. doi:10.3390/genes13060957.

Level	Question/Issue	Results	Example of Pairs of Propositions
			• An unknown individual is the major contributor of the DNA mixture.

Adapted with permission from Hicks et al., 2022.[67]

FSSPs should assess case information in a transparent way and should consider the effect of human factors relating to bias, risk management, and efficacy. An example is the United Kingdom Forensic Science Service model for case assessment and interpretation.[68] This formalized model focuses on **customer** requirements from a scientific perspective by using the principles of interpretation. The analyst is encouraged to think about—and document—the propositions considered that address the case questions and the expected results of the items tested. This process also helps to protect the analyst from post-hoc rationalization of their findings.

As part of case assessment, an investigative agency may deem a case inactive or closed. For example, a complainant may not be willing or able to testify. However, DNA testing could still be useful if a DNA profile might be suitable for entry in a DNA database (see ***Sec. 3.5.2*: *Database Comparisons***). In other instances, a case may be adjudicated without DNA results. FSSPs may have testing policies that are influenced by the status of the case, limit how many items can be tested, or determine whether items are analyzed for DNA at all.

Recommendation 3.1: To promote balance and transparency in DNA analysis, forensic science service providers should apply the "principles of interpretation" and should understand the "hierarchy of propositions."

3.2.2 Pre-Comparison Phase

If the case information suggests that DNA analysis could be valuable for the factfinder or if the FSSP or customer policy dictates, the case will be assigned to an analyst or a team of individuals. Items identified as part of the examination plan during the case management phase will be inventoried, examined, screened, or sampled. The collected samples will be processed in line with the FSSP's procedures to develop a DNA profile. The resulting DNA profile will be assessed for quality (e.g., potential artifacts) and then be evaluated to determine if the DNA profile is suitable for comparison to known reference samples from POIs.

[67] Hicks T, Buckleton J, Castella V, Evett IW, Jackson G. A Logical Framework for Forensic DNA Interpretation. *Genes (Basel)*. 2022; 13(6):957. doi:10.3390/genes13060957.

[68] Cook R, Evett IW, Jackson G, Jones PJ, Lambert JA. A Model for Case Assessment and Interpretation. *Science & Justice*. 1998; 38(3):151-6. doi:10.1016/S1355-0306(98)72099-4; Jackson G, Jones PJ. Case Assessment and Interpretation. *Wiley Encyclopedia of Forensic Science*. 2009; 2:483-96. doi:10.1002/9780470061589.fsa124.

During the case management phase, the FSSP and submitting party begin formulating the relevant propositions. Prior to a comparison, the analyst may update these propositions based on the DNA profile that is developed (see ***Sec. 3.5.3.1: Formulating Propositions in an LR Framework***). If there is no putative perpetrator, or if the putative perpetrator profile is unavailable, then the analyst may upload the profile to a searchable DNA database or provide investigators with possible explanations for the DNA results (see ***Sec. 5.3.2.4: Possible Explanations for DNA Results***). Some cases, or some samples within a case, may not proceed past the pre-comparison phase.

3.2.3 Comparison Phase

DNA analysts should consider whether appropriate reference profiles are available for comparison. If a POI profile is available and the forensic profile[69] is suitable for comparison, the analyst will assess whether the profiles are similar or dissimilar to each other. Depending on the FSSP's policy, sample-to-sample[70] profile comparisons may also be made and reported in the absence of a POI profile.

The FSSP's protocol and method of interpretation employed will dictate the process for comparing profiles. Methods of interpretation could be manual (sometimes called binary or visual comparisons), automated in a software program (i.e., PGS), or a combination of the two. If the profiles appear different, the analyst may *exclude* the POI (see ***Sec. 4.5.4: Exclusion Language).*** If the profiles appear similar, the analyst will quantify the evidentiary value of this similarity (see ***Chapter 4: Quantitative and Qualitive Ways to Express DNA Results***).

DNA analysts in the United States may be familiar with the terms *included* or *consistent with* to describe the results of this process. However, for reasons that are discussed further in ***Chapter 4: Quantitative and Qualitive Ways to Express DNA Results***, any qualitative term for the outcome of a **DNA comparison** can be misleading. When an analyst cannot tell if the profiles are similar or not, a protocol should dictate what is to be reported (see ***Sec. 4.5.2: Issues with the Term "Inconclusive"***). Manual comparisons offer significant challenges due to the difficulty in defining what *similar* or *dissimilar* mean. Software-based approaches offer several advantages, and suggestions for a process of moving from visual to software-based comparisons are offered in ***Sec. 3.7: Moving Towards PGS***.

[69] A *forensic profile* is any DNA profile derived from the analysis of a trace or item collected as part of a criminal investigation that has an unknown or questioned origin. This may also be referred to as a *forensic unknown profile*.
[70] Sample-to-sample are comparisons of forensic profiles within or between cases.

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3.2.4 Post-Comparison Phase

If the DNA analyst obtains new case information or additional questions arose during the investigation prompting the need for additional examinations or comparisons (e.g., a new elimination reference is obtained), then the analyst may need to perform additional comparisons or reanalyze or reinterpret a forensic profile. If the FSSP does not have a specific technology validated (e.g., Y-chromosome short tandem repeats [Y-STRs], mitochondrial DNA [mtDNA], single nucleotide polymorphisms [SNPs]), or when retesting by a different FSSP is requested, the FSSP should send these items to an external FSSP for analysis.

3.3 Important Human Factors Considerations in Interpretation

There is considerable variability in how FSSPs, and even different analysts within the same FSSP, approach DNA analysis and interpretation.[71] Variability also exists in how an analyst may approach tasks at different time points, including variability as their experience level changes. This variation makes the topic of DNA interpretation and the potential for bias, error, and the influence of other human factors so important to understand.

This chapter provides specific examples of decision points where variability may occur and the possible upstream and downstream effects of this variability. Although this chapter cannot address all sources of variability, cognitive bias, or error, we present several concepts that underpin some human factors considerations that are key to understanding and improving interpretation issues in DNA analysis. ***Chapter 8: Quality Assurance/Quality Control***, ***Chapter 9: Education, Training, and Professional Credentialing***, and ***Chapter 10: Management*** discuss how management, resources, culture, and the legal system in which FSSPs operate can influence variability, cognitive bias, and error.

3.3.1 Discretionary Decisions Versus Standard Operating Procedures

Many decisions throughout the course of DNA analysis are discretionary, which means they are left to the FSSP or the analyst. While there are national and international standards and guidelines by which an FSSP may be **audited**, they only set forth *what* an FSSP should do, not *how* they should accomplish it.[72] Some decisions (e.g., polymerase chain reaction [PCR] cycle number, injection parameters) are non-discretionary procedural determinations based on validation and

[71] Brinkac LM, Richetelli N, Davoren JM, Bever RA, Hicklin RA. DNAmix 2021: Laboratory Policies, Procedures, and Casework Scenarios Summary and Dataset. *Data Brief*. 2023; 48:109150. doi:10.1016/j.dib.2023.109150; Butler JM, Kline MC, Coble MD. NIST Interlaboratory Studies Involving DNA Mixtures (MIX05 and MIX13): Variation Observed and Lessons Learned. *Forensic Science International: Genetics*. 2018; 37:81-94. doi:10.1016/j.fsigen.2018.07.024; Dror IE, Hampikian G. Subjectivity and Bias in Forensic DNA Mixture Interpretation. *Science & Justice*. 2011; 51(4):204-8. doi:10.1016/j.scijus.2011.08.004; Hicklin RA, Richetelli N, Emerick BL, Bever RA, Davoren JM. Variation in Assessments of Suitability and Number of Contributors for DNA Mixtures. *Forensic Science International: Genetics*. 2023; 65:102892. doi:10.1016/j.fsigen.2023.102892.

[72] Federal Bureau of Investigation (FBI). *Quality Assurance Standards for Forensic DNA Testing Laboratories*. 2020. https://le.fbi.gov/file-repository/forensic-qas-070120.pdf/view; International Organization for Standardization (ISO). *General Requirements for the Competence of Testing and Calibration Laboratories, ISO/IEC 17025:2017*. 2017. https://www.iso.org/standard/66912.html.

a thorough assessment prior to implementation within a standard operating procedure (SOP) (see ***Sec. 8.3.2*: *Validation and Requirements to Implement New Practices***). Other decisions may be left to the discretion of the analyst during analysis and interpretation. Regardless, FSSPs should document and outline in an SOP which decisions are procedural and which are discretionary.

SOPs should be built upon knowledge garnered during **internal validation**. Validations attempt to test samples reflective of casework, and SOPs use this information to provide a framework for analysts' tasks and steps. Clear SOPs arm analysts with the tools needed to make educated and empirically supported decisions and reduce inter- and intra-analyst variability. But discretion remains important. SOPs should provide the flexibility to adapt to changing conditions and empower analysts to decide what should be done for a particular case or sample depending on the unique situation.

Discretionary decisions are particularly useful since testing is a nuanced and complex process where it is not possible to know all the testing considerations, scenarios, or circumstances in advance of testing. Discretionary decisions allow analysts to make informed choices based upon the nature of the case and the sample(s) to be tested. However, there is a trade-off that comes with this flexibility. These decision points can be a source of inter- and intra-analyst variability and may be prone to biases.

Examples of discretionary decisions may include:

- Which samples to test and the number of samples to test during serology and DNA profiling
- Whether to concentrate a DNA extract prior to quantitation or amplification
- Whether to perform additional amplifications to confirm results
- Which genetic analyzer parameter to use (e.g., injection time, run voltage)
- Whether to assume the presence of a known contributor
- Whether to adjust default software settings for a given sample or interpretation (analysis software or PGS software)
- Which propositions to consider (e.g., one or more POIs as co-contributors)

Depending on the technical review process of an FSSP, choices made by the primary analyst may be assessed during the technical review process, in part to determine if the appropriate items were tested and evaluated given the questions in the case. However, confirmation bias can occur during this type of review. The *Forensic Handwriting Examination and Human Factors Report*[73]

[73] Expert Working Group for Human Factors in Handwriting Examination. Forensic Handwriting Examination and Human Factors: Improving the Practice through a Systems Approach. NIST IR 8282r1. National Institute of Standards and Technology; 2021. doi:10.6028/NIST.IR.8282r1

addressed human factors issues related to the review process, and ***Sec. 8.5*: *Blinded Reviews*** expands on this topic. Differences in opinions over such decisions may be a source of conflict between analysts. Such conflicts may be difficult to resolve, slow the review process, delay the reporting of results, and lead to a drain of FSSP resources. Discussions or disagreements could also lead the primary analyst to feel pressured to acquiesce to avoid elevation to the **Technical Leader (TL)**. Analysts may then overfocus on the flagged decisions when processing the next case, to the detriment of other important considerations.[74]

As FSSPs implement and use new methods and technologies, decision points may oscillate between discretionary and procedural. Users' familiarity with new methods and technology may increase flexibility in discretionary decisions. For example, the requirement for consultation and approval from the TL at certain steps of a new method may later be relaxed. In other instances, flexibility may decrease or change to procedural decisions, which should be supported through updated SOPs and validation data. Additionally, as technology has advanced, there has been a trend towards outsourcing critical decision points to software programs.

Software programs may improve efficiency and consistency and reduce some potential sources of bias. However, overreliance on these systems can result in analysts conducting or testifying about work that they have a less robust scientific understanding about than previous methods. Even with the aid of technology, it is often still the analyst's discretion to accept or reject the information produced by such software. It is important to conduct periodic reviews of discretionary decision points to determine if they are still necessary and effective. In addition, the extent of inter- and intra-analyst variability introduced by these decisions should be established. Whenever possible, the variability introduced should be minimized or removed.

FSSPs should evaluate the downstream effects of discretionary decisions and the level of inter- and intra-analyst variation this procedural freedom introduces. This assessment should also include which decision points, if any, are sources of disagreement during the technical review process.

3.3.2 Decision Justification and Recording: Transparency and Documentation

The Federal Bureau of Investigation Quality Assurance Standards (FBI QAS) defines analytical documentation as "the documentation of procedural notes, controls, and instruments used; observations made; results of tests performed; and charts, graphs, photos, and other documentation generated which are used to support the analyst's conclusions."[75] In addition,

[74] Jeanguenat AM, Budowle B, Dror IE. Strengthening Forensic DNA Decision Making through a Better Understanding of the Influence of Cognitive Bias. *Science & Justice*. 2017; 57(6):415-20. doi:10.1016/j.scijus.2017.07.005.

[75] Federal Bureau of Investigation (FBI). *Quality Assurance Standards for Forensic DNA Testing Laboratories*. 2020. https://le.fbi.gov/file-repository/forensic-qas-070120.pdf/view. p. 2.

Standard 11 of the FBI QAS establishes the minimum requirements FSSPs should meet for taking and maintaining case notes and related analytical documentation. This standard broadly addresses the need for "sufficient documentation for each technical analysis to support the report conclusions such that another qualified individual can evaluate what was done and interpret the data."[76] However, the level of documentation and the extent of note taking is often discretionary, which can result in inter- and intra-FSSP variability.

Non-discretionary decisions should be clearly delineated in an FSSP's SOPs, which should be made available to interested parties, including the prosecution, defense, and other criminal justice partners. When discretion is afforded to an analyst, documentation in the case notes or case file is necessary to record the reasons or justifications behind the decisions made. SOPs alone do not provide enough information regarding the discretionary decisions made for a particular case or sample.

Documentation should include both the action and the justification for it. This is particularly important when a decision significantly impacts downstream analysis (e.g., artifact removal that impacts NOC determination; post-hoc removal of a **locus** from the evaluation). As discretionary decisions become more routine and analysts become more experienced with a particular method or workflow, they may become complacent in the level of documentation they provide. This complacency should be guarded against through robust SOPs requiring clear documentation of these decisions and the analyst's reasoning.

Previous human factors in forensic science reports have discussed the need for transparency and the scientific and legal value of documenting the handling and processing of evidence;[77] this applies to DNA interpretation as well. Documentation should be completed contemporaneously to the actions being performed and accurately reflect any examination and interpretation that was performed, as well as the basis of the conclusions reached.

When choosing between options and processes available during casework, the analyst should record their choice and the reasons for it. Any post-hoc changes to initial conclusions should also be explicitly documented (see **Sec. *3.6*: *Post-Comparison Interpretation: Modifying an Interpretation After a Comparison***). In addition, it should be clear to anyone reviewing the case file whether any steps were repeated and if so, why. A record of rejected data and data generated during troubleshooting, even if not used, should also be maintained. Accurately reflecting the sequence of examination processes and opinions provides the opportunity for a case reviewer to

[76] Ibid. Standard 11, p. 31.

[77] Expert Working Group for Human Factors in Handwriting Examination. Forensic Handwriting Examination and Human Factors: Improving the Practice through a Systems Approach. NIST IR 8282r1. National Institute of Standards and Technology; 2021. doi:10.6028/NIST.IR.8282r1 ; Expert Working Group on Human Factors in Latent Print Analysis. Latent Print Examination and Human Factors: Improving the Practice through a Systems Approach. National Institute of Standards and Technology; 2012. doi:10.6028/NIST.IR.7842

consider the potential impact any influencing factors may have had at the time of the recorded action or decision.

Documentation may be recorded in a variety of ways such as narrative, tabular, or simple checklists (see ***Sec. 5.4*: *Report Formats***). In general, the extent to which an analyst may provide additional case- or sample-specific documentation often relates to the complexity of the interpretation.

In addition to any physical records or notes generated, FSSPs should maintain all electronic data produced during analysis (e.g., raw sample files, PGS run files, version of software used), regardless of whether they are used to render a conclusion. Much of the responsibility of record keeping may be offloaded to a Laboratory Information Management System (LIMS) that provides clear audit trails. For efficiency, the FSSP could implement drop-down lists or a list of standard annotations for all analysts to use. This would also simplify the process for analysts and provide guidance on how to document the *what* and the *why* of decisions that are made (see **Callout Box 3.1**).

Technical reviewers should be able to understand the primary analyst's decision-making process. Documenting the primary analyst's logic can minimize the time-consuming back and forth. Documentation should reflect not only the reasoning or justification of decisions but also the sequence in which discretionary decisions were made.

Thorough documentation also assists analysts, auditors, and criminal justice partners. If an analyst is required to testify to a DNA result, it may be months or even years between their interpretation of the evidence and data and their testimony. An analyst should not be expected to remember every processing and interpretation decision and the reasoning behind those decisions in every case. Attempts to remember these details in the absence of adequate records could be incorrect or biased by later information.[78] This is especially critical in post-conviction reviews of DNA analyses or when evaluating whether additional testing should be conducted with new technologies. If a clear record of the analyst's interpretations, decisions, and justifications is maintained, the analyst will be in the best position to testify to their decision-making process. Furthermore, others who may rely on those records later will be in a better position to make accurate assessments.

Improved documentation also leads to improved transparency, which serves independent reviewers who may be unfamiliar with an FSSP's or analyst's discretionary practices as well as

[78] For example, *confirmation bias* (see ***Sec. 2.4*: *Cognitive Bias***) and *hindsight bias* – the tendency to think that decisions or outcomes were more obvious later, once the final decision or judgment has been rendered. Fischhoff B. Hindsight Not Equal to Foresight: The Effect of Outcome Knowledge on Judgment under Uncertainty. *Quality & Safety in Health Care*. 2003; 12(4):304-11. doi:10.1136/qhc.12.4.304.

criminal justice partners as they work towards a more accurate understanding of the scientific evidence in criminal proceedings.

Recommendation 3.2: DNA analysts should maintain a detailed record of the reasoning, justification, and sequence of decisions not dictated by the forensic science service provider's protocols (i.e., discretionary decisions).

Callout Box 3.1: Barriers to Documentation and Ways to Overcome Them

Documentation can be a valuable tool for an analyst and other **end-users** of a case file; however, there can be barriers to increasing the expected level of documentation. These could include:

- **Obtaining analyst buy-in:** Because of the potential increase in time and effort required to document additional information or decisions made during the process, analysts may be resistant to this change. Also, since accrediting bodies do not specify the level of documentation, FSSPs and analysts may be reluctant to make a change that is not mandatory.
- **Limitations of existing systems in place for analysis and documentation:** Depending on what method(s) an FSSP uses to create and retain documentation, it may or may not be easy to make changes (e.g., paper-based documentation is more flexible than a LIMS, for which any new documentation policies may require changes to the software).
- **Inconsistency between analysts:** More documentation is not the only goal—the increase in documentation should be as consistent between analysts in an FSSP as possible. Without clear guidelines, the information an analyst records in a case file, especially relating to reasoning behind an interpretation, will vary between analysts within an FSSP, as well as between cases for a single analyst. It can be difficult to define required documentation, and there may be a lack of agreement as to what constitutes sufficient documentation.
- **Increase in length of case file/report:** The presence of additional documentation would increase the size of the case file and potentially the report, depending on how or where the information is recorded. This naturally results in more information to be reviewed during technical review; however, this does not necessarily add to the review time.
- **Fear of critique:** An analyst may fear that the additional justification or reasoning for a decision would then be available to a reviewer (internal or external), end-user, and factfinder to critique.

While these barriers may make the implementation of increased documentation more difficult, they are not insurmountable. Possible ways to overcome the challenges described above could include:

- Simplifying the process for analysts with the use of:
  - Drop-down lists in software with commonly used options
  - Checklists with commonly used options
  - Defined list of acronyms/abbreviations used in the case file
- Making recommendations to software developers on what could aid the documentation process
- Highlighting the benefits (e.g., transparency, assists technical reviewer, aids recall of reasoning in the future, available for external review)

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- Providing pre-printed labels for paper-based systems or "stamps" for electronic systems to reduce time spent on written documentation
- Annotating documents electronically
- Maintaining easily accessible electronic audit records of any changes made during interpretation (e.g., artifact labeling change)
- Training analysts to use the methods chosen by the FSSP

It is important to remember that increased documentation and implementing processes to overcome these barriers do not create a system that is immune from human factors. Simply documenting something does not mean that it is correct. For example, if an FSSP chooses to use a pre-populated drop-down list during artifact editing, an analyst could inadvertently select the wrong artifact description without realizing it. There could also be the risk of automating a process so much that the analyst is not critically evaluating and reviewing their own work and decisions. Any new methods being used to increase documentation should be monitored to ensure they are serving their purpose without causing issues or risk to the quality of the casework.

3.3.3 Cognitive and Contextual Bias and Impacts on Decision Points in DNA Analysis

A background on how cognitive bias is to be understood in the context of this report can be found in ***Sec. 2.4: Cognitive Bias***. Some aspects of DNA analysis have a greater potential for bias to affect the analyst's ultimate opinion about the DNA results. This chapter focuses primarily on human and cognitive factors and sources of case-specific information (i.e., information contained within the data itself, the reference material, and contextual information).

Examples of decision points that may be inappropriately influenced by contextual information are presented in ***Appendix 3.1.*** Each decision point corresponds to a decision point in the Organization of Scientific Area Committees for Forensic Science (OSAC) Human Forensic Biology Subcommittee's Human Forensic DNA Analysis Process Map[79] (see ***Sec. 2.3: A Forensic DNA Analysis Process Map***).

3.3.4 Contextual Information Management

The primary objective for any CIM method is to shield analysts from task-irrelevant contextual information or, at a minimum, track the impact of that information, while ensuring they still have access to information necessary to their task. Methods for CIM include:

- **(Linear) sequential unmasking**[80]

[79] Organization of Scientific Area Committees (OSAC). *Human Forensic DNA Analysis Process Map*. 2022. https://www.nist.gov/system/files/documents/2022/05/05/OSAC%20Forensic%20Biology%20Process%20Map_5.5.22.pdf.

[80] Archer MS, Wallman JF. Context Effects in Forensic Entomology and Use of Sequential Unmasking in Casework. *Journal of Forensic Sciences*. 2016; 61(5):1270-7. doi:10.1111/1556-4029.13139; Dror IE, Kukucka J. Linear Sequential Unmasking-Expanded (LSU-E): A General Approach for Improving Decision Making as Well as Minimizing Noise and Bias. *Forensic Science International: Synergy*. 2021; 3:100161. doi:10.1016/j.fsisyn.2021.100161; Dror IE, Thompson WC, Meissner CA, Kornfield I, Krane D, Saks MJ, Risinger M. Letter to the Editor- Context Management Toolbox: A Linear Sequential Unmasking (LSU) Approach for Minimizing Cognitive Bias in Forensic Decision Making. *Journal of Forensic Sciences*. 2015; 60(4):1111-2. doi:10.1111/1556-4029.12805; Langenburg G. Addressing Potential Observer Effects in Forensic Science:

- A context manager model[81]
- Blind peer review[82] (see ***Sec. 8.5*: *Blinded Reviews***)
- Independent checking[83]

How these methods work in practice is presented in papers that describe CIM for FSSP-based bloodstain pattern analysis,[84] firearms examination,[85] and document examination.[86] In addition to these practical strategies, DNA analysis can be strengthened by training in cognitive bias and establishing quality assurance/quality control (QA/QC) procedures to mitigate bias.[87] A practical, research-based tool that is easily incorporated into training, analysts' workflows, or the FSSPs' QA/QC framework is freely available.[88]

For CIM procedures to succeed, FSSPs first need to identify information as task-relevant or task-irrelevant (see **Table 3.2**). Many decisions in forensic DNA analysis *require* contextual or case information for analysts to make accurate and appropriate decisions. Examples of information include:

- The alleged activities for evidence collection personnel to perform appropriate evidence recovery/sampling of the relevant items or areas
- Relevant contextual information to formulate appropriate propositions (e.g., knowledge of consensual partners)
- DNA profiles of assumed or expected contributors
- The possibility of related individuals' involvement or presence in the case or DNA profile

A Perspective from a Forensic Scientist Who Uses Linear Sequential Unmasking Techniques. *Australian Journal of Forensic Sciences*. 2017; 49(5):548-63. doi:10.1080/00450618.2016.1259433; Quigley-McBride A, Dror IE, Roy T, Garrett BL, Kukucka J. A Practical Tool for Information Management in Forensic Decisions: Using Linear Sequential Unmasking-Expanded (LSU-E) in Casework. *Forensic Science International: Synergy*. 2022; 4:100216. doi:10.1016/j.fsisyn.2022.100216.

[81] Almazrouei MA, Dror IE, Morgan RM. The Forensic Disclosure Model: What Should Be Disclosed to, and by, Forensic Experts? *International Journal of Law, Crime and Justice*. 2019; 59:100330. doi:10.1016/j.ijlcj.2019.05.003; Found B, Ganas J. The Management of Domain Irrelevant Context Information in Forensic Handwriting Examination Casework. *Science & Justice*. 2013; 53(2):154-8. doi:10.1016/j.scijus.2012.10.004; Mattijssen EJ, Kerkhoff W, Berger CEH, Dror IE, Stoel RD. Implementing Context Information Management in Forensic Casework: Minimizing Contextual Bias in Firearms Examination. *Science & Justice*. 2016; 56(2):113-22. doi:10.1016/j.scijus.2015.11.004.

[82] Ballantyne KN, Edmond G, Found B. Peer Review in Forensic Science. *Forensic Science International*. 2017; 277:66-76. doi:10.1016/j.forsciint.2017.05.020; Robertson CT, Kesselheim AS. *Blinding as a Solution to Bias: Strengthening Biomedical Science, Forensic Science, and Law*. Elsevier Academic Press: London, UK, 2016.

[83] Osborne NKP, Taylor MC. Contextual Information Management: An Example of Independent-Checking in the Review of Laboratory-Based Bloodstain Pattern Analysis. *Science & Justice*. 2018; 58(3):226-31. doi:10.1016/j.scijus.2018.01.001.

[84] Ibid.

[85] Mattijssen EJ, Kerkhoff W, Berger CEH, Dror IE, Stoel RD. Implementing Context Information Management in Forensic Casework: Minimizing Contextual Bias in Firearms Examination. *Science & Justice*. 2016; 56(2):113-22. doi:10.1016/j.scijus.2015.11.004.

[86] Found B, Ganas J. The Management of Domain Irrelevant Context Information in Forensic Handwriting Examination Casework. *Science & Justice*. 2013; 53(2):154-8. doi:10.1016/j.scijus.2012.10.004.

[87] Jeanguenat AM, Budowle B, Dror IE. Strengthening Forensic DNA Decision Making through a Better Understanding of the Influence of Cognitive Bias. *Science & Justice*. 2017; 57(6):415-20. doi:10.1016/j.scijus.2017.07.005.

[88] Quigley-McBride A, Dror IE, Roy T, Garrett BL, Kukucka J. A Practical Tool for Information Management in Forensic Decisions: Using Linear Sequential Unmasking-Expanded (LSU-E) in Casework. *Forensic Science International: Synergy*. 2022; 4:100216. doi:10.1016/j.fsisyn.2022.100216.

Stripping task-relevant information from the analysts can produce worse outcomes than allowing them to review it and result in uninformed decisions being made within a vacuum (see **Callout Box 3.2**). To ensure analysts have access to all useful information while also mitigating potential bias, FSSPs can employ a case manager to determine the order in which analysts receive information about a case—from the most to least essential or relevant information. The analyst then receives pieces of information in that pre-determined order and updates their analyses and decisions accordingly, while clearly documenting the reasons for any changes in their approach or opinions.[89]

Determining what is task-relevant and task-irrelevant can vary between types of DNA evidence, cases, and analyses. In addition, some forms of task-irrelevant information cannot be separated from the data needed by the analyst. At times, the very nature of the evidence in question may elicit a particular feeling or response. The circumstances of a case along with the viewing of disturbing photographs from crime scenes have been shown to affect fingerprint comparisons.[90] Subsequent decisions may be influenced by the context in which the evidence is presented. Consider examining an elderly victim's underwear for semen in a sexual assault case or a child's clothing for blood in a homicide case. These situations may elicit more of an emotional response than sampling a water bottle left in a stolen vehicle.

Table 3.2 provides examples of task-relevant and task-irrelevant information that FSSPs could consider when designing CIM protocols. Information that is relevant for one task will not be relevant during other tasks. For example, the time between the alleged activity and evidence collection is not relevant when determining NOC, but it might be relevant when determining which items to test. Some information will not be relevant for any DNA analysis tasks and should be avoided. For example, the fact that a POI was identified through CCTV footage has no relevance to a DNA analyst.

[89] Dror IE, Thompson WC, Meissner CA, Kornfield I, Krane D, Saks MJ, Risinger M. Letter to the Editor- Context Management Toolbox: A Linear Sequential Unmasking (LSU) Approach for Minimizing Cognitive Bias in Forensic Decision Making. *Journal of Forensic Sciences*. 2015; 60(4):1111-2. doi:10.1111/1556-4029.12805; Quigley-McBride A, Dror IE, Roy T, Garrett BL, Kukucka J. A Practical Tool for Information Management in Forensic Decisions: Using Linear Sequential Unmasking-Expanded (LSU-E) in Casework. *Forensic Science International: Synergy*. 2022; 4:100216. doi:10.1016/j.fsisyn.2022.100216.

[90] Dror IE, Péron AE, Hind S-L, Charlton D. When Emotions Get the Better of Us: The Effect of Contextual Top-Down Processing on Matching Fingerprints. *Applied Cognitive Psychology*. 2005; 19(6):799-809. doi:10.1002/acp.1130; Osborne NKP, Zajac R. An Imperfect Match? Crime‐Related Context Influences Fingerprint Decisions. *Applied Cognitive Psychology*. 2015; 30(1):126-34. doi:10.1002/acp.3180.

Table 3.2: Non-exhaustive examples of generally task-relevant and task-irrelevant information associated with different tasks within the analytic process. Exceptions will exist depending on the case circumstances.

Task	Examples of Task-Relevant Information	Examples of Task-Irrelevant Information
Case Assessment	• Details connecting the item to the crime scene or perpetrator	• Victim appeared unemotional during the sexual assault examination • POI's previous criminal history • POI confessed to crime • POI's appearance • The POI was identified from CCTV images • Third-party eyewitness accounts of events
Sample/Item Selection	• Time between the alleged activity and evidence collection	
Proposition Formulation NOC **Deconvolution**	• POI in possession of, or with access to, the item • Where an item was recovered • Prior consensual partner reported • If an individual had legitimate access to the scene/item • The possibility of relatives on scene • The possibility that a relative may be a POI	

The many sources of information, the disparate impacts that bias can have at each step in the process, and the need for analysts to have some—but not all—information to perform their tasks means that there is no one-size-fits-all strategy for addressing cognitive bias in forensic DNA interpretation. Instead, a more nuanced approach is needed, and FSSPs should consider their individual workflows and processes to determine what might be appropriate mitigation strategies to fit their needs. FSSPs should develop CIM policies and procedures, and they should document adherence to these. Documentation could include checklists, audit trails, sign-off sheets, and having the case manager document the information that was removed.

Recommendation 3.3: Forensic science service providers should assess their processes to identify potential sources of bias in the interpretation and comparison of DNA evidence. Forensic science service providers should implement written policies and procedures to mitigate these sources of bias.

3.3.5 Understanding Upstream and Downstream Effects

Variability, repeatability, and reliability of the data can have significant impact on the value of evidence. For example, the DNA fragments in low-template samples may not amplify reliably. Since each FSSP holds stewardship over their own SOPs, each conducts their own validations to determine what SOP or technology to implement. If the SOP of one FSSP, for example, includes conditions for increased sensitivities (e.g., increased injection times) that are substantively different than another, then the same minor component may be detected in one FSSP but not in

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another. Another example is when different FSSPs have differing target amplification amounts. These simple examples highlight the interplay between the number of amplifiable DNA molecules, the FSSP procedures, the results, and how the result can vary between FSSPs by virtue of FSSP or procedural decisions rather than by virtue of their interpretative practices.

Callout Box 3.2: DNA Testing in Queensland – A Call Against the Silo Effect[91]

The murder of Shandee Blackburn played an integral part in exposing the failing of the Queensland forensic DNA laboratory, leading to a Queensland Commission of Inquiry. The Commission of Inquiry determined that the methods, systems, and processes the laboratory used did not, in many ways, measure up to best practices established in forensic DNA testing. It is thought that the Queensland forensic DNA laboratory system had focused more on throughput and quick reporting than examining the scientific quality of the results being reported.

In the Queensland forensic DNA laboratory structure, the different processes (i.e., evidence collection, analytical processing, interpretation and reporting, and database upload) were siloed into separate and individual practices that operated apart from one another. In this structure, analysts proceeded without any case context through the establishment of a worklist system and sampling system worklist.

The Final Report: Commission of Inquiry into Forensic DNA Testing in Queensland[92] identifies more than 100 recommendations, but there are three main areas where contextual information would have allowed analysts to use their judgment to determine if results were in concordance with their expectation. For example, a swab from a pool of blood should yield an interpretable DNA profile. In many cases within the Queensland forensic DNA laboratory, it did not, and there were no contextual checks or balances to identify this problem.

Three areas where the silo effect and lack of contextual information failed the system include:

1. Analytical sample processing. Sample testing proceeded in a worklist system with no contextual information provided to the analyst. In this system, without contextual information, many unnecessary samples were being fully tested and other vital samples were being shelved to aid in faster turnaround times.
2. Quantitation cutoffs. Samples that yielded a concentration below 0.0088 ng/µL were not transferred from the analytical processing team to the interpretation and reporting team in their worklist. Thus, no reporting analysts ever saw the quantitative results or that these samples were processed. In this event, there were samples that should have returned a result given the nature of the biological sample/material from which they were derived, and the low concentration should have raised concern with analysts. However, these samples were never reviewed by the reporting analyst. Additionally, samples that would be expected to yield a considerable amount of DNA (e.g., swabs collected from a pool of blood) failed to pass the quantitation cutoff, but without contextual information the analyst was unaware of the intuitive expectation.
3. Interpretation and technical review. Within a case, each of the individual samples may be interpreted and reviewed by multiple analysts, meaning every case file was the combination of half a dozen or more minds with each sample having a primary interpreting analyst and different technical review analysts. If a statement for court needed to be made, it could be yet another analyst's opinion. This led to an increase in disagreements in previous views and confusion and frustration on the part of the law enforcement investigators. Additionally, an

[91] Sofronoff W. *Final Report: Commission of Inquiry into Forensic DNA Testing in Queensland*. 2022. https://www.health.qld.gov.au/__data/assets/pdf_file/0036/1196685/final-report-coi-dna-testing-qld-dec-2022.pdf.

[92] Ibid.

entire case review by one reporting analyst only took place if all samples had to be collected into a report for court, which only occurred in approximately 10% of the cases. The failure to cohesively review the case file in its entirety exacerbated the previous issues where samples were not yielding expected results based on the nature of the biological material from which they were derived.[93]

The Queensland case is a stark example of multiple systems failing to ensure the quality of science required by the legal system. In these failures reported in the Commission of Inquiry, it should be noted that there were analysts that tried to speak out against the silo effect within the structure of the Queensland forensic DNA laboratory and who pointed out scientific inadequacies and problems. It should also be noted within this report that there were many indications of where issues within the Queensland forensic DNA laboratory were not dealt with in a way that demonstrated a focus on quality assurance.[94]

This example highlights some risks of removing necessary contextual information within a case (see ***Sec. 3.3.4*: Contextual Information Management**).

Recommendation 3.4: Forensic science service providers should evaluate and understand the impact that procedural decisions have on DNA results and their interpretation. With this knowledge, DNA analysts should be able to understand the effect certain treatments will have on downstream decisions and outcomes within the DNA analysis workflow.

3.4 Generating a DNA Profile and Determining Suitability for Interpretation

An FSSP's validated workflow of the interpretation process will not always be as linear as the Human Forensic DNA Analysis Process Map depicts.[95] The various factors at play and the numerous decision points in all FSSPs collectively contribute to the final reported result. The extent to which inter-laboratory variation impacts conclusions is hard to characterize, though attempts to do so have been[96] and continue to be made.[97] The following sections discuss factors and decision points that contribute to the current variability across and within FSSPs (e.g., methods of NOC assessment, interpretation approaches). Some factors may influence whether an allele is detected (e.g., input template, number of PCR cycles). Other factors relate to how detected data is handled (e.g., applying an analytical threshold, filtering artifacts, assessing NOC).

[93] Ibid.

[94] Ibid.

[95] Organization of Scientific Area Committees (OSAC). *Human Forensic DNA Analysis Process Map*. 2022. https://www.nist.gov/system/files/documents/2022/05/05/OSAC%20Forensic%20Biology%20Process%20Map_5.5.22.pdf.

[96] Butler JM, Kline MC, Coble MD. NIST Interlaboratory Studies Involving DNA Mixtures (MIX05 and MIX13): Variation Observed and Lessons Learned. *Forensic Science International: Genetics*. 2018; 37:81-94. doi:10.1016/j.fsigen.2018.07.024.

[97] Hicklin RA, Richetelli N, Emerick BL, Bever RA, Davoren JM. Variation in Assessments of Suitability and Number of Contributors for DNA Mixtures. *Forensic Science International: Genetics*. 2023; 65:102892. doi:10.1016/j.fsigen.2023.102892.

As profiles increase in complexity, more advanced tools are needed to assess interpretation suitability. FSSPs should be able to provide specific guidance for how to assess suitability, reduce variability in suitability assessments, and improve the quality of mixture interpretations. Doing so across FSSPs using PGS is especially important, as the use of software-based approaches may be misunderstood as removing all previously recognized sources of variability and bias.

3.4.1 Generating the EPG

The DNA analysis process begins with the decision of which items to select for testing. From there, DNA is extracted and quantified prior to its amplification through PCR. Following amplification, the DNA is separated via **capillary electrophoresis (CE)**, and a raw data output file is generated, which may then be converted to a readable file by a DNA analysis software program. Amplified DNA fragments are displayed as a series of peaks arranged according to size. Generally, the higher the peak (represented by relative fluorescence units [RFU]), the more DNA was detected.

The chance of detecting a particular allele will be influenced by the following:[98]

1. Number of cells or DNA molecules collected
2. Volume or concentration of DNA extract used for amplification
3. Injection or PCR conditions
4. Analytical threshold

DNA analysis software programs that aid in the generation of the EPG to be interpreted use sizing information to "call" and label the detected fragments as alleles for each genetic location, or STR marker, targeted during amplification. At this step, the analysis software may also flag peaks as potentially non-allelic, or artifactual (see **Sec. *3.4.4*: *Editing the EPG: Artifact Determination***). In displaying and organizing the detected DNA fragments, the analysis software ultimately generates the EPG, complete with labels.

[98] Bregu J, Conklin D, Coronado E, Terrill M, Cotton RW, Grgicak CM. Analytical Thresholds and Sensitivity: Establishing RFU Thresholds for Forensic DNA Analysis. *Journal of Forensic Sciences*. 2013; 58(1):120-9. doi:10.1111/1556-4029.12008; Butler JM. *Advanced Topics in Forensic DNA Typing: Methodology*. Elsevier Academic Press: San Diego, CA, 2011. ; Butler JM, Buel E, Crivellente F, McCord BR. Forensic DNA Typing by Capillary Electrophoresis Using the ABI Prism 310 and 3100 Genetic Analyzers for STR Analysis. *Electrophoresis*. 2004; 25(10-11):1397-412. doi:10.1002/elps.200305822; Ensenberger MG, Lenz KA, Matthies LK, Hadinoto GM, Schienman JE, Przech AJ, Morganti MW, Renstrom DT, Baker VM, Gawrys KM, Hoogendoorn M, Steffen CR, Martin P, Alonso A, Olson HR, Sprecher CJ, Storts DR. Developmental Validation of the PowerPlex® Fusion 6C System. *Forensic Science International: Genetics*. 2016; 21:134-44. doi:10.1016/j.fsigen.2015.12.011; Ludeman MJ, Zhong C, Mulero JJ, Lagace RE, Hennessy LK, Short ML, Wang DY. Developmental Validation of Globalfiler PCR Amplification Kit: A 6-Dye Multiplex Assay Designed for Amplification of Casework Samples. *International Journal of Legal Medicine*. 2018; 132(6):1555-73. doi:10.1007/s00414-018-1817-5; Meakin GE, Kokshoorn B, van Oorschot RAH, Szkuta B. Evaluating Forensic DNA Evidence: Connecting the Dots. *WIREs Forensic Science*. 2020; 3(4):e1404. doi:10.1002/wfs2.1404; Moretti TR, Baumstark AL, Defenbaugh DA, Keys KM, Brown AL, Budowle B. Validation of STR Typing by Capillary Electrophoresis. *Journal of Forensic Sciences*. 2001; 46(3):661-76. doi:10.1520/jfs15019j; Moretti TR, Baumstark AL, Defenbaugh DA, Keys KM, Smerick JB, Budowle B. Validation of Short Tandem Repeats (STRs) for Forensic Usage: Performance Testing of Fluorescent Multiplex STR Systems and Analysis of Authentic and Simulated Forensic Samples. *Journal of Forensic Sciences*. 2001; 46(3):647-60. doi:10.1520/JFS15018J; Rakay CA, Bregu J, Grgicak CM. Maximizing Allele Detection: Effects of Analytical Threshold and DNA Levels on Rates of Allele and Locus Drop-Out. *Forensic Science International: Genetics*. 2012; 6(6):723-8. doi:10.1016/j.fsigen.2012.06.012.

Once the EPG is generated, an analyst or software system edits the data to determine what is displayed (e.g., allele assignment, artifact flags, allele peak height, stutter labels) by retaining, removing, or adding information. Downstream interpretations and deconvolutions will be affected by what peak information is retained or removed and could be influenced by what labels or edits are displayed and easily viewable to the analyst or reviewers.

Some interpretation systems will apply an analytical threshold (AT), which removes the peak labels that fall below a certain RFU (see **Callout Box 3.3**). Although these peaks are unlabeled, they are still visible, and the peak height and allele sizing information is still accessible to the analyst. ATs are applied to avoid interpreting noise as a true allele, but the binary classification discards information.[99] Some interpretation software systems model noise directly.[100] They can be used without setting and validating an AT.

Callout Box 3.3: Setting Appropriate ATs

Ideally, the FSSP's DNA analysis and interpretation system produces sensitive and specific results as shown through internal validation.

- **What is an AT?** An AT is an RFU value under which peaks on the EPG are not readily distinguished from noise and, therefore, are not labeled by the analysis software. This is the height that validation testing indicates is rarely the result of noise (see **Fig. 3.1**). Peaks below the AT are more typical of noise than of alleles.

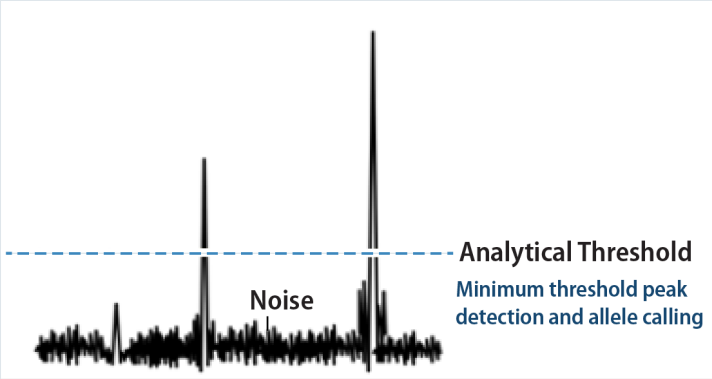

Figure 3.1: The AT.

Figure adapted from Butler, 2009 and reprinted with permission.[101]

[99] Bregu J, Conklin D, Coronado E, Terrill M, Cotton RW, Grgicak CM. Analytical Thresholds and Sensitivity: Establishing RFU Thresholds for Forensic DNA Analysis. *Journal of Forensic Sciences*. 2013; 58(1):120-9. doi:10.1111/1556-4029.12008; Organization of Scientific Area Committees (OSAC). *Standards for Determining Analytical and Stochastic Thresholds for Application to Forensic DNA Casework Using Electrophoresis Platforms, Version 1.0. OSAC Proposed Standard 2021-S-0003*. 2022. https://www.nist.gov/system/files/documents/2022/06/06/OSAC%202021-S-0003%20Standards%20for%20Determining%20Analytical%20and%20Stochastic%20Thresholds_OPEN%20COMMENT%20VERSION.pdf.

[100] Perlin MW, Legler MM, Spencer CE, Smith JL, Allan WP, Belrose JL, Duceman BW. Validating TrueAllele® DNA Mixture Interpretation. *Journal of Forensic Sciences*. 2011; 56(6):1430-47. doi:10.1111/j.1556-4029.2011.01859.x.

[101] Butler JM. *Fundamentals of Forensic DNA Typing*. Elsevier Academic Press: San Diego, CA, 2009. doi:10.1016/C2009-0-01945-X.

- **How the AT is derived:** The AT should be set to mitigate labeling of noise rather than to minimize detection of artifacts.[102] Noise is random and can be located anywhere along the x-axis of the EPG without regard to the position of other peaks. Artifacts, in contrast, are often systematically detected in the same location as other peaks. For example, pull-up artifacts align with allele peaks of another color channel, while dye artifacts are in the same location across profiles. ATs may have a uniform value across all dyes or may be dye specific.
- **Risks of assigning an extreme AT:** The AT is the signal threshold that is typically determined by evaluating the signal intensities for regions of an EPG where analysts do not anticipate signal from DNA or artifacts. The higher the AT, the higher the chance that an allele will be missed. The lower the AT, the greater the risk of non-alleles being called true signals. Methods that can help in deciding how to balance this trade-off include inspection of detection error trade-off and receiver operating curves.[103]
- **Should data visually observed under an AT be used?** FSSPs should first consider that their AT may be set too high for the data being analyzed. If an AT is set well above the limit of detection, it may not be directly correlated to the baseline noise of the instrument in use, and it would be worth reassessing the AT and how it is being used within the FSSP. If an AT is required by an FSSP, it is usually because the current interpretation system does not model noise directly. Many FSSPs using an AT and manually assigning NOC are influenced by the observation of visible peaks below their established AT (see ***Sec. 3.4.7.4*: *Human Factors in NOC Assessment***). But the purpose of an AT is to standardize interpretations at a desired trade-off between false negative and false positive risks. A properly set AT, by definition, means that only peaks observed above AT are appropriate for interpretation.

Recommendation 3.5: Forensic science service providers should validate and apply analysis settings and laboratory processes that generate and characterize as much informative data as possible with the available instrumentation and technology.

3.4.2 Suitability Considerations

Based on the EPG, analysts may decide that a profile or a portion of it is suitable for interpretation. Suitability is based on factors such as DNA quantity, the number of alleles, allelic peak heights, peak height ratios, reproducibility of replicates, percent contribution, template amount (for FSSPs using PGS), possibility of drop-out, and ambiguity related to the NOC.[104] One study

[102] Taylor D, Bright JA, McGoven C, Hefford C, Kalafut T, Buckleton J. Validating Multiplexes for Use in Conjunction with Modern Interpretation Strategies. *Forensic Science International: Genetics*. 2016; 20:6-19. doi:10.1016/j.fsigen.2015.09.011.

[103] Rakay CA, Bregu J, Grgicak CM. Maximizing Allele Detection: Effects of Analytical Threshold and DNA Levels on Rates of Allele and Locus Drop-Out. *Forensic Science International: Genetics*. 2012; 6(6):723-8. doi:10.1016/j.fsigen.2012.06.012.

[104] Brinkac LM, Richetelli N, Davoren JM, Bever RA, Hicklin RA. DNAmix 2021: Laboratory Policies, Procedures, and Casework Scenarios Summary and Dataset. *Data Brief*. 2023; 48:109150. doi:10.1016/j.dib.2023.109150; Hicklin RA, Richetelli N, Emerick BL, Bever RA, Davoren JM. Variation in Assessments of Suitability and Number of Contributors for DNA Mixtures. *Forensic Science International: Genetics*. 2023; 65:102892. doi:10.1016/j.fsigen.2023.102892.

reported that 90% of their participants use a maximum NOC as a part of their suitability assessment.[105]

By only interpreting components of mixtures, FSSPs may increase the number of samples suitable for interpretation. For instance, when interpreting an entire profile, an FSSP may have a suitability cap of four contributors. However, interpreting only certain components of a five- or six-person mixture may be permissible. It should be clearly documented in the case file which components are being interpreted and used for comparison. Statistical models and associated software are also available to interpret components of higher-order mixtures.[106] FSSPs that parse out suitable components of mixtures will then report the results of their POI comparison(s) for only the components deemed interpretable.

The criteria used to isolate only components of a mixture for interpretation should be clear in the FSSP's SOP to minimize inconsistencies in interpretation. The method should be thoroughly validated and tested, and different analysts should be tasked with applying the established method to the same set of mixture profiles to determine what, if any, variation in conclusions exists (see ***Sec. 8.3.2*: *Validation and Requirements to Implement New Practices***).

An SOP needs to be clear and prescriptive to guide analysts when making suitability decisions. Limited discrimination potential of a profile or deconvolved genotypes can lead to the inclusion of non-contributors. This possibility should be explored and characterized during mixture validation studies, regardless of the method of interpretation. When such a profile is compared to a POI, the potential for an erroneous or misleading conclusion may be considered too great.

Software-based methods that compare the forensic profile to a set of profiles of simulated true donors and non-contributors (e.g., database likelihood ratio [DBLR], or true donors and non-donor likelihood ratio [LR] distributions[107]) can aid analysts when determining profile suitability. They may also help to promote consistency among analysts and FSSPs.

Analysts should make profile suitability determinations *prior* to viewing a POI profile to reduce the biasing potential the reference profile may have. However, in some instances, the complexity, and therefore suitability, of a profile is not fully realized until a statistical analysis has been completed. For example, LRs larger than 1 are expected to occur for first-order relatives due to

[105] Brinkac LM, Richetelli N, Davoren JM, Bever RA, Hicklin RA. DNAmix 2021: Laboratory Policies, Procedures, and Casework Scenarios Summary and Dataset. *Data Brief*. 2023; 48:109150. doi:10.1016/j.dib.2023.109150.

[106] Slooten K. A Top-Down Approach to DNA Mixtures. *Forensic Science International: Genetics*. 2020; 46:102250. doi:10.1016/j.fsigen.2020.102250.

[107] Kelly H, Kerr Z, Cheng K, Kruijver M, Bright JA. Developmental Validation of a Software Implementation of a Flexible Framework for the Assignment of Likelihood Ratios for Forensic Investigations. *Forensic Science International: Reports*. 2021; 4:100231. doi:10.1016/j.fsir.2021.100231; Schuerman C, Kalafut T, Buchanan C, Sutton J, Bright JA. Using the Nondonor Distribution to Improve Communication and Inform Decision Making for Low LRs from Minor Contributors in Mixed DNA Profiles. *Journal of Forensic Sciences*. 2020; 65(4):1072-84. doi:10.1111/1556-4029.14306.

the sharing of alleles rather than because the relative(s) have truly contributed to the mixture. When this occurs, the results from statistical analysis with and without conditioning on related contributors may need to be evaluated. The DNA analyst should evaluate multiple sets of propositions.[108]

An FSSP may deem the sample unsuitable for interpretation based on which reference profiles are available and whether conditioning on, or assuming the presence of, a certain combination of contributors is possible or beneficial. The case notes should reflect the point at which a profile was deemed unsuitable and should clearly state the reasoning behind the decision.

Factors that increase the complexity of interpretation lead to more variability in interpretation and in judgments of suitability and outcomes of comparisons (see **Callout Box 3.4** and ***Sec. 3.4.7.2: Complexity in NOC Estimation***).

Callout Box 3.4: Factors that Contribute to the Complexity and Challenging Nature of DNA Profiles

NOC: Generally, as NOC increases, so too does the complexity and challenging nature of the interpretation.

Peak height imbalances: Could indicate additional contributors or reflect low quantity or quality of amplified input template. This may also indicate a potential mixture of first-order relatives; however, case information will often be necessary to elucidate this.

Low levels of starting material or degraded template: Leads to larger peak height imbalance, higher levels of **allelic drop-out**, and higher expressions of stutter. Preferential amplification may also occur.

Allele uncertainty: Trace contributors may fall in the same allele peak height range as stutter and artifactual peaks. Appropriate references for conditioning an interpretation may be lacking (e.g., known contributors, elimination references). Stochastic effects, degradation, and inhibition impact allele peak heights and heterozygote peak height balance. Micro-variants and primer binding site mutations may be difficult to confirm without additional testing (e.g., replicate amplifications, sequencing).

Examples of questions that may assist in establishing the complexity of a DNA profile include:

- What is the quality or quantity of the DNA present?
- Should relatives be considered?
- Should conditioning on an assumed contributor be used?
- Is there any ambiguity regarding the assigned NOC?
- How resolvable are the different mixture components?

[108] American Academy of Forensic Sciences Standards Board. *ASB Standard 041, First Edition 2021: Formulating Propositions for Likelihood Ratios in Forensic DNA Interpretations*. 2021. https://www.aafs.org/sites/default/files/media/documents/041_Std_Ballot02.pdf ; Gill P, Hicks T, Butler JM, Connolly E, Gusmao L, Kokshoorn B, Morling N, van Oorschot RAH, Parson W, Prinz M, Schneider PM, Sijen T, Taylor D. DNA Commission of the International Society for Forensic Genetics: Assessing the Value of Forensic Biological Evidence - Guidelines Highlighting the Importance of Propositions. Part II: Evaluation of Biological Traces Considering Activity Level Propositions. *Forensic Science International: Genetics*. 2020; 44:102186. doi:10.1016/j.fsigen.2019.102186; Gittelson S, Kalafut T, Myers S, Taylor D, Hicks T, Taroni F, Evett IW, Bright JA, Buckleton J. A Practical Guide for the Formulation of Propositions in the Bayesian Approach to DNA Evidence Interpretation in an Adversarial Environment. *Journal of Forensic Sciences*. 2016; 61(1):186-95. doi:10.1111/1556-4029.12907.

Recommendation 3.6: To reduce the variability in how DNA analysts determine profile suitability, forensic science service providers should validate, set, implement, and routinely reassess suitability boundaries.

3.4.3 Setting Expectations Based on the Sample Type

It is important for analysts to be cognizant of the upstream decisions that were made prior to the generation of the EPG. These decisions may impact not only the profile, but also the expectation for the sample. Some common expectations are:

- a full DNA profile will be developed if a sufficient amount of DNA is present in the sample;
- a partial DNA profile with allelic drop-out may be obtained if degradation or inhibition has been indicated;
- a mixture of at least two contributors will be obtained based on quantitation data and the ratio of male to autosomal DNA detected based on quantitation data; and
- a single-source DNA profile will be obtained from a known reference sample.

In these examples, the expectations are grounded in empirical validation data and quantitation results. When the data does not meet these expectations, the results serve to alert the analyst that a potential issue exists that may influence downstream analysis and results. For example, if a mixture profile was obtained from a reference sample, the analyst may proceed to resample or obtain another reference.

Case information provided by the submitting party can also have an impact on the analyst's expectations about the evidence (see ***Sec. 2.4.1*: *Cognitive Bias and Forensic DNA Interpretation***). If a sample is labeled as blood, the analyst might expect that the profile will be from a single source. This analyst may be more willing to call a disputed peak "high stutter" (thus removing it from the profile) and not evaluate the DNA profile as a mixture. Alternatively, analysts may expect certain specimens to be mixtures (e.g., samples taken from firearms) based on their previous experience with similar items.

The context in which a POI profile is received can influence the interpretation process in subtle ways. For example, the comparison of a mixture profile to a POI profile may be influenced by its characterization (e.g., the complainant's consensual partner). The analyst may attribute little value to whether the elimination reference is represented in the mixture profile. Conversely, analysts may expend greater time and effort for interpretations and comparisons they have deemed important.

This publication is available free of charge from: https://doi.org/10.6028/NIST.IR.8503

The findings from other samples within the case (or merely knowing that a POI profile from a suspect is available for comparison) may contribute to the effort to make an association. The influence may be as subtle as changing the assigned NOC by one; however, that change may determine or alter suitability, the nature of the association, and the statistical value assigned to the results.

Spending extra time and effort on comparisons that may be important is not necessarily problematic. However, when borderline suitability decisions might well be influenced by potentially biasing information, the FSSP should take extra steps to review such decisions (e.g., blind peer review) (see ***Sec. 3.3.4*: Contextual Information Management**).

3.4.4 Editing the EPG: Artifact Determination

With or without an AT (see **Callout Box 3.3**), review of an EPG is necessary to determine if any labeled peaks are potentially non-allelic. Non-allelic peaks are often referred to as *artifacts*. Artifacts may be inherent in the amplified product and therefore reproducible (e.g., stutter and non-specific amplification products), or they may be introduced by the instrument and, therefore, not reproducible (e.g., spikes).[109]

To prevent a POI's reference profile from influencing artifact determinations, the analyst should assess, edit, and document edits of the EPG prior to any comparisons.[110] Establishing criteria for the interpretation of non-allelic peaks is necessary since the decision to designate a questioned peak as an artifact influences downstream interpretation. FSSPs often establish criteria for artifact assessment during the validation of a new typing kit or instrument. Typically, they use pristine DNA that produces high-quality profiles. Assessing and identifying non-allelic peaks, or artifacts, in casework samples is often more difficult than in validation and training. Furthermore, subtle variations in artifacts across different lot numbers of the same STR typing kit platform may be observed. A manufacturer's new reagent lot may generate more, or different, non-allelic peaks.

The characteristic behaviors of some artifacts can aid in the classification of peaks as allelic or non-allelic. For example, *stutter* is a well-described byproduct of amplification.[111] In contrast to

[109] Butler JM. *Advanced Topics in Forensic DNA Typing: Interpretation*. Elsevier Academic Press: San Diego, CA, 2014.

[110] Federal Bureau of Investigation (FBI). *Quality Assurance Standards for Forensic DNA Testing Laboratories*. 2020. https://le.fbi.gov/file-repository/forensic-qas-070120.pdf/view; Scientific Working Group on DNA Analysis Methods (SWGDAM). *SWGDAM Interpretation Guidelines for Autosomal STR Typing by Forensic DNA Testing Laboratories*. 2017. https://www.swgdam.org/_files/ugd/4344b0_3f94c9a6286048c3924c58e2c230e74e.pdf.

[111] Bright JA, Taylor D, Curran JM, Buckleton J. Developing Allelic and Stutter Peak Height Models for a Continuous Method of DNA Interpretation. *Forensic Science International: Genetics*. 2013; 7(2):296-304. doi:10.1016/j.fsigen.2012.11.013; Brookes C, Bright JA, Harbison S, Buckleton J. Characterising Stutter in Forensic STR Multiplexes. *Forensic Science International: Genetics*. 2012; 6(1):58-63. doi:10.1016/j.fsigen.2011.02.001.

other artifacts, every EPG will contain apparent stutter peaks, and their shape is often indistinguishable from that of true alleles.

Depending on whether an FSSP uses a manual or probabilistic approach for mixture interpretation, stutter peaks may or may not be removed when editing the EPG. FSSPs may also use a hybrid approach in which stutter peaks are visually filtered on the EPG, but the data from those peaks are still used for downstream interpretation.

Appropriate stutter thresholds or models are critical because stutter peaks can be mistaken for allelic ones. The improper handling of stutter, and other artifacts, has the potential to cause false inclusions or exclusions.[112] FSSPs should strive for consistency when designating whether a peak is artifactual. In addition, manufacturers of STR typing kits should strive for consistency throughout production of commercial kits.

3.4.5 Technology-Assisted Artifact Determination

Technology that aids in artifact interpretation or automatic filtering is preferable to manual approaches. By modeling and predicting the range of artifact behaviors encountered in casework, a probabilistic approach to artifacts can account for much of the uncertainty. Machine learning methods such as neural networks[113] may help remove the influence of contextual information, reducing inter- and intra-analyst variability in artifact assessment.

Even with these newer approaches, some analyst review and decision-making are still required, and even commonly encountered artifacts can be mistaken for true alleles by both software programs and analysts. FSSPs therefore should implement clear and specific rules for removing a peak from further interpretation. The rules should be applied prior to performing a comparison to a POI reference profile (see ***Sec. 3.6*: Post-Comparison Interpretation: Modifying an Interpretation After a Comparison**). Additionally, the FSSP should clearly define when analyst discretion is permitted. Some discretion will likely always be a part of the EPG editing process, regardless of the approach, as analysts still need to use their training and expertise to recognize when the method employed for artifact filtering is not accurately reflecting the observed profile. When discretion is allowed, the FSSP should require analysts to document their justification and reasoning in the case record.

[112] Jeanguenat AM, Budowle B, Dror IE. Strengthening Forensic DNA Decision Making through a Better Understanding of the Influence of Cognitive Bias. *Science & Justice*. 2017; 57(6):415-20. doi:10.1016/j.scijus.2017.07.005.

[113] Lin M-H, Lee S-I, Zhang X, Russell L, Kelly H, Cheng K, Cooper S, Wivell R, Kerr Z, Morawitz J, Bright JA. Developmental Validation of FaSTR™ DNA: Software for the Analysis of Forensic DNA Profiles. *Forensic Science International: Reports*. 2021; 3:100217. doi:10.1016/j.fsir.2021.100217; Taylor D, Kitselaar M, Powers D. The Generalisability of Artificial Neural Networks Used to Classify Electrophoretic Data Produced under Different Conditions. *Forensic Science International: Genetics*. 2019; 38:181-84. doi:10.1016/j.fsigen.2018.10.019.

3.4.6 Human Factors in Artifact Determination

Currently, most FSSPs manually assess artifacts with filtering rules of varying complexity. These rules reflect a compromise between the **probability** of falsely labeling an artifact peak as an allele and the risk of incorrectly removing an allelic peak from downstream interpretation. However, because of the difficulty in capturing the range and uncertainty associated with artifacts, filtering "rules" are often guidelines that allow analyst discretion. This discretion can result in variable determinations based on training and experience as well as contextual information.

FSSPs may have a maximum allowable NOC beyond which a sample will be deemed uninterpretable. For example, an FSSP might choose to interpret only profiles with at most four contributors. As a result, removing a potential allele as an artifact may be the difference between an interpretable and an uninterpretable profile. These downstream consequences should not unduly influence the analyst making an artifact determination. While the impact of identification, or misidentification, of artifacts is typically minimal for robust single-source profiles, it is greater when dealing with complex, higher-order mixture profiles.

Analyst fatigue may exist when reviewing numerous profiles during data analysis, especially when the profiles are more complex (e.g., mixtures or samples with numerous artifacts). Depending on whether an FSSP uses a blind or non-blind second review of the analyzed data, confirmation bias may affect artifact review. To minimize bias (i.e., "painting the target"[114]), analysts should not look at a questioned contributor's profile during the initial assessment of the forensic profile(s). Using software tools to assign the NOC and model and filter artifacts reduces, but does not eliminate, the potential for bias. The analyst still may have the authority to override the initial artifact assessment performed by the software. There should be an audit trail of this decision-making to comply with current standards.[115]

3.4.7 Assigning NOC

Once data have been generated and artifacts designated, the next step in the process typically involves an assessment of the NOC (or range of NOC) that best explains the DNA profile. This analysis relies on the laws of inheritance where the detection of more than two alleles at multiple STR markers indicates the sample contains DNA from multiple individuals. Allelic information, when combined with additional information from the EPG including inter- and intra-locus peak height balances, allele counts, and allele frequencies, forms the basis for the assignment of the NOC for a DNA profile. Strategies for deciding what NOC range to consider vary from manual

[114] Thompson WC. Painting the Target around the Matching Profile: The Texas Sharpshooter Fallacy in Forensic DNA Interpretation. *Law, Probability and Risk*. 2009; 8(3):257-76. doi:10.1093/lpr/mgp013.

[115] American National Standards Institute/Academy Standards Board. *ANSI/ASB Standard 022: Standard for Forensic DNA Analysis Training Programs*. 2019. https://www.aafs.org/sites/default/files/media/documents/022_Std_e1.pdf.

assessments (visual inspection of the EPG) to sophisticated probabilistic, machine-learning, and decision-tree-software-based approaches.[116]

3.4.7.1 Manual Methods for NOC Assignment

Provisional NOC estimates are obtained by the maximum allele count (MAC) method. The method involves focusing on the locus with the greatest number of peaks exceeding the AT, counting the number of peaks, dividing the total peaks by two, and rounding up. At times, a combination of MAC, an assessment of the total allele count, and a visual evaluation of peak-height-ratio differences justify the addition of one or two contributors to the MAC estimate; however, it remains unclear if visual inspection renders consistent NOC estimations across analysts over time.[117] In cases in which the initial inspection renders NOC estimates that are too high, a reevaluation may be warranted, with all the interpretation requirements associated with reevaluations (see ***Sec. 3.6: Post-Comparison Interpretation: Modifying an Interpretation After a Comparison***).

3.4.7.2 Complexity in NOC Estimation

Two competing factors make the MAC method only a provisional means by which to assign NOC. First, extraneous signals from noise and artifacts may be indistinguishable from true alleles in low-template DNA samples or in samples containing low amounts of DNA from one or more contributors. For example, the peak heights of stutter products increase with respect to the parent alleles as the DNA template decreases.[118] This may not align with the stutter models and thresholds established by FSSPs, which typically use high-template DNA. Failing to remove all stutter and other extraneous peaks when editing the EPG can impact the provisional NOC assignment. In addition, stutter ratios are known to increase with the number of uninterrupted STR units,[119] though stutter ratios and their filters are often based on a per locus (rather than per allele) evaluation of stutter ratios. Second, allelic drop-out increases in low-template DNA

[116] Benschop CCG, van der Linden J, Hoogenboom J, Ypma R, Haned H. Automated Estimation of the Number of Contributors in Autosomal Short Tandem Repeat Profiles Using a Machine Learning Approach. *Forensic Science International: Genetics*. 2019; 43:102150. doi:10.1016/j.fsigen.2019.102150; Grgicak CM, Karkar S, Yearwood-Garcia X, Alfonse LE, Duffy KR, Lun DS. A Large-Scale Validation of NOCIt's a Posteriori Probability of the Number of Contributors and Its Integration into Forensic Interpretation Pipelines. *Forensic Science International: Genetics*. 2020; 47:102296. doi:10.1016/j.fsigen.2020.102296; Kruijver M, Kelly H, Cheng K, Lin MH, Morawitz J, Russell L, Buckleton J, Bright JA. Estimating the Number of Contributors to a DNA Profile Using Decision Trees. *Forensic Science International: Genetics*. 2021; 50:102407. doi:10.1016/j.fsigen.2020.102407.

[117] Hicklin RA, Richetelli N, Emerick BL, Bever RA, Davoren JM. Variation in Assessments of Suitability and Number of Contributors for DNA Mixtures. *Forensic Science International: Genetics*. 2023; 65:102892. doi:10.1016/j.fsigen.2023.102892.

[118] Duffy KR, Gurram N, Peters KC, Wellner G, Grgicak CM. Exploring STR Signal in the Single- and Multicopy Number Regimes: Deductions from an in Silico Model of the Entire DNA Laboratory Process. *Electrophoresis*. 2017; 38(6):855-68. doi:10.1002/elps.201600385.

[119] Brookes C, Bright JA, Harbison S, Buckleton J. Characterising Stutter in Forensic STR Multiplexes. *Forensic Science International: Genetics*. 2012; 6(1):58-63. doi:10.1016/j.fsigen.2011.02.001.

samples or low-template contributors. This drop-out could result in an underestimated NOC because the computed MAC will be too small.[120]

Both factors can occur simultaneously, when indications of drop-out are masked by the elevation of stutter at low-template levels. Conversely, as the true NOC increases, so too does allele sharing and, ultimately, allele masking. The presence of related individuals exacerbates the risk of understating the MAC and the NOC.[121]

Although the NOC is not usually the ultimate value of interest for its own sake,[122] it is relevant in that ranges that are too low and too narrow (e.g., a single underestimated value) can have a large effect on downstream comparison. The range of NOCs will be informed by the analyst's initial manual NOC assessment. The method chosen for assigning NOC will be driven by the operational needs, the complexity of reporting and testifying to the data, and the FSSP's SOPs. Most FSSPs assign NOC (or range of NOC) that best explains the evidence. For FSSPs that use a probabilistic workflow, but do not use a tool to assist with NOC, interpretations under variable NOC are still possible by performing multiple deconvolutions.

3.4.7.3 Technology-Assisted NOC Estimations

There are two general types of emerging NOC systems: those that compute a single NOC, and those that provide a probability distribution for NOC. Unlike continuous LR software systems that predominantly rely on models based on similar biological (i.e., allele frequencies) and chemometric (i.e., increase in signal intensity with number of DNA molecules) principles, NOC algorithms vary vastly in their structure,[123] and it is imperative that FSSPs validate the method before implementation (see ***Sec. 8.3.1*: *Variation, Reliability, and Validity***).

[120] Norsworthy S, Lun DS, Grgicak CM. Determining the Number of Contributors to DNA Mixtures in the Low-Template Regime: Exploring the Impacts of Sampling and Detection Effects. *Legal Medicine*. 2018; 32:1-8. doi:10.1016/j.legalmed.2018.02.001.

[121] Kruijver M, Curran JM. The Number of Alleles in DNA Mixtures with Related Contributors. *Forensic Science International: Genetics*. 2022; 61:102748. doi:10.1016/j.fsigen.2022.102748.

[122] Slooten K, Caliebe A. Contributors Are a Nuisance (Parameter) for DNA Mixture Evidence Evaluation. *Forensic Science International: Genetics*. 2018; 37:116-25. doi:10.1016/j.fsigen.2018.05.004.

[123] For more information on how these systems were developed and the differences between them, see Benschop CCG, van der Linden J, Hoogenboom J, Ypma R, Haned H. Automated Estimation of the Number of Contributors in Autosomal Short Tandem Repeat Profiles Using a Machine Learning Approach. *Forensic Science International: Genetics*. 2019; 43:102150. doi:10.1016/j.fsigen.2019.102150; Grgicak CM, Duffy KR, Lun DS. The a Posteriori Probability of the Number of Contributors When Conditioned on an Assumed Contributor. *Forensic Science International: Genetics*. 2021; 54:102563. doi:10.1016/j.fsigen.2021.102563; Grgicak CM, Karkar S, Yearwood-Garcia X, Alfonse LE, Duffy KR, Lun DS. A Large-Scale Validation of NOCIt's a Posteriori Probability of the Number of Contributors and Its Integration into Forensic Interpretation Pipelines. *Forensic Science International: Genetics*. 2020; 47:102296. doi:10.1016/j.fsigen.2020.102296; Haned H, Pène L, Lobry JR, Dufour AB, Pontier D. Estimating the Number of Contributors to Forensic DNA Mixtures: Does Maximum Likelihood Perform Better Than Maximum Allele Count? *Journal of Forensic Sciences*. 2011; 56(1):23-8. doi:10.1111/j.1556-4029.2010.01550.x; Marciano MA, Adelman JD. PACE: Probabilistic Assessment for Contributor Estimation- a Machine Learning-Based Assessment of the Number of Contributors in DNA Mixtures. *Forensic Science International: Genetics*. 2017; 27:82-91. doi:10.1016/j.fsigen.2016.11.006.

3.4.7.4 Human Factors in NOC Assessment

Even with the shift towards probabilistic mixture deconvolution, manual assessment of NOC is still common in the forensic DNA community, as many software programs still require the user to select an initial NOC.[124] Case information can influence the estimated NOC (as shown by case three of DNA MIX13,[125] which involved the possibility of a relative and consensual intercourse with a romantic partner in a sexual assault case), DNA profiles of assumed contributors, analyst experience, and additional information such as the appearance of peaks visible below the AT. These factors tend to make manual NOC estimation highly variable. With respect to case information and assumed contributors, the analyst should clearly document the case information that was known and considered during the interpretation steps (see ***Sec. 5.5.2: Purpose of the Analysis, Case Information, and Contextual Information Management Procedures***).

FSSPs that use an AT and assign NOC manually should also closely evaluate whether it is appropriate to consider below-threshold peaks during the NOC assessment and subsequent interpretation steps. The validation of an AT should establish a reasonable threshold for distinguishing between noise and true signal, and not be a threshold that seeks to minimize artifact detection (see **Callout Box 3.4**). If, ultimately, an analyst who considers below-AT peaks at any point should clearly indicate which peaks are considered and the degree to which those peaks influenced the interpretative conclusions. For example, an analyst might note that peaks below AT were considered at locus SE33 in arriving at a NOC of 4. If, as a practice, analysts within an FSSP commonly use peaks under AT to inform NOC, then the AT itself (or the method, assumptions, or k-factor used to set it) may need to be reevaluated.

3.4.8 Conditioning

An assumed contributor is an individual whose genetic contribution is reasonably expected to be present in a profile due to the nature, origin, and context of the sample. The genotypes for that individual are then assumed to be present in the DNA mixture, and the interpretation is conditioned on this assumption. This individual may be represented in the mixture profile to varying degrees (i.e., their contributions do not need to be fully expressed). The term *assumed contributor* is sometimes used interchangeably with *known contributor*. However, conditioning an interpretation on an assumed contributor is dictated by an FSSP's SOP, and the individual's contributions are never known with casework samples. They are only assumed.

[124] Bauer DW, Butt N, Hornyak JM, Perlin MW. Validating TrueAllele® Interpretation of DNA Mixtures Containing up to Ten Unknown Contributors. *Journal of Forensic Sciences*. 2020; 65(2):380-98. doi:10.1111/1556-4029.14204; Gill P, Benschop C, Buckleton J, Bleka O, Taylor D. A Review of Probabilistic Genotyping Systems: EuroForMix, DNAStatistX and STRMix™. *Genes (Basel)*. 2021; 12(10):1559. doi:10.3390/genes12101559.

[125] Butler JM, Kline MC, Coble MD. NIST Interlaboratory Studies Involving DNA Mixtures (MIX05 and MIX13): Variation Observed and Lessons Learned. *Forensic Science International: Genetics*. 2018; 37:81-94. doi:10.1016/j.fsigen.2018.07.024.

Contributions from a known contributor can be assumed for bodily samples collected from the individual (internal and external); for clothing collected directly from the individual; or for items known to have been in direct contact with the individual (for example, a cell phone or a steering wheel). An interpretation may also be conditioned on the assumption that an individual's DNA is present based on contextual information (for example, a consensual partner or an elimination reference profile).

Interpretations conditioned on known contributors only apply to mixture profiles where the analyst is inferring reasonable genotype combinations, either manually or using PGS, to explain the genotypes foreign to the known contributor. In an LR framework, the DNA of the known contributor may be assumed to be present under both propositions and is therefore termed a *conditioning profile*.[126] In some instances, assuming a contributor will have no impact on the resulting interpretation of the remaining profile(s). For example, a two-person mixture where both contributors are fully resolved (e.g., a robust 90:10 mixture) will not change significantly since the respective genotypes of each contributor are obvious based on relative mixture proportions. However, the use of conditioning is typically based on the known case information rather than the resolvability of the genetic profiles.

There is currently no requirement or standard that dictates when an analyst should apply conditioning. The Scientific Working Group on DNA Analysis Methods (SWGDAM) only states as a Core Element that "any criteria (e.g., assumptions such as number of contributors and/or the presence of a known contributor) used in the interpretation of a mixed DNA sample shall be supported by the data and shall be defined and documented."[127] Although it is impossible to cover all possibilities, an FSSP's SOP should state as explicitly as possible the circumstances under which it is appropriate to assume the presence of an individual, and the method of applying that assumption should be clear.

FSSPs using PGS may deconvolve a mixture profile and generate an LR for the known contributor to determine if the assumption accurately reflects the data. If the LR is above an established threshold for the deconvolution, then the deconvolution is repeated and conditioned on the assumed individual. When a known individual is assumed to be a contributor to a profile, this assumption must be reported.

[126] Bright JA, Coble M. *Forensic DNA Profiling: A Practical Guide to Assigning Likelihood Ratios*. CRC Press: Boca Raton, Florida, 2019. doi:10.4324/9780429001017.

[127] Scientific Working Group on DNA Analysis Methods (SWGDAM). *SWGDAM Interpretation Guidelines for Autosomal STR Typing by Forensic DNA Testing Laboratories*. 2017. https://www.swgdam.org/_files/ugd/4344b0_3f94c9a6286048c3924c58e2c230e74e.pdf.

3.4.9 Deconvolution

Following NOC assignment, and if applicable, conditioning, the next step in the interpretation of the DNA profile involves an evaluation of the allelic information (i.e., size and height) to determine the genotype combinations that are possible for each locus. When a DNA profile is a mixture, this process is referred to as **deconvolution**. For FSSPs employing PGS, it may be possible to run the deconvolution at the same time as the POI LR calculation. However, this approach is not recommended since an analyst cannot evaluate the deconvolution diagnostics before the comparison is done. As a result, the acceptance of a PGS evaluation, and the diagnostic outputs, may be influenced by the LR results.

3.4.9.1 Manual Deconvolution

Some FSSPs use a manual deconvolution approach in which genotype combinations are inferred using binary rules or thresholds. Thresholds indicate where reliable data will fall. They enable the analyst to develop reasonable expectations for a given profile. Data falling below a threshold, such as a stochastic threshold, may be deemed not usable. Such thresholds are set during an FSSP's internal validation and are based on the performance of a given STR typing workflow (i.e., STR typing kit, thermal cycler parameters, genetic analyzer settings, and genotyping or analysis software).

Manual approaches can be labor intensive, are prone to inter-analyst variability, and do not consider as much information in the DNA profile as PGS does.[128] Manual approaches cannot model the probability of allelic drop-out (i.e., missing genetic information) or drop-in (i.e., exogenous DNA introduced into a sample). Amplification of low-level DNA samples often results in stochastic effects such as heterozygote peak height imbalance (where two sister alleles exhibit significantly different peak heights) or allelic drop-out. Stochastic effects, by definition, involve a random variable or chance.[129] Thus, their impact can vary across an entire profile, which increases the challenge of addressing these effects manually. Using replicate amplifications may mitigate some of the uncertainty caused by stochastic effects.

Certain loci, and even certain alleles within a locus, may be preferentially amplified. Setting a stochastic threshold establishes the point above which allelic drop-out is unusual for a single-source profile. For manual deconvolution, the same threshold is routinely applied to mixture samples, but shared alleles from multiple contributors may be stacked on top of each other, and a stochastic threshold may no longer accurately represent the **likelihood** of drop-out for a

[128] Coble MD, Bright JA. Probabilistic Genotyping Software: An Overview. *Forensic Science International: Genetics*. 2019; 38:219-24. doi:10.1016/j.fsigen.2018.11.009.

[129] Timken MD, Klein SB, Buoncristiani MR. Stochastic Sampling Effects in STR Typing: Implications for Analysis and Interpretation. *Forensic Science International: Genetics*. 2014; 11:195-204. doi:10.1016/j.fsigen.2014.03.015.

corresponding sister allele. Additionally, regardless of whether a peak is, say, 1 RFU or 100 RFUs below a stochastic threshold, it is treated the same.

Indeed, all thresholds used in a manual approach do not address the uncertainty that exists when a questioned peak falls just above or below the cutoff, whether that threshold pertains to allele detection, stutter, or drop-out. An analyst's recognition of the limitations of the manual approach may lead the analyst to adjust their interpretation and deconvolution. Depending on the FSSP's SOP, the analyst may have discretion to override the binary framework (e.g., consider peaks below AT, discount peaks slightly above stutter thresholds as elevated stutter). This discretion might improve accuracy in some cases, but it contributes to some of the variability observed with manual mixture deconvolution.[130]

Despite these limitations, there are times when a manual interpretation is unlikely to be problematic or overly variable, assuming drop-out is improbable: single-source profiles and mixture profiles for which contributors can be deduced without ambiguity (based on mixture ratios or the availability of a known contributor profile).

3.4.9.2 Assessing PGS Diagnostics

Many FSSPs have incorporated PGS, which uses sophisticated computer software, to aid the analyst's interpretation.[131] PGS allows for greater use of the profile data, and it can be used on challenging and complex profiles that are unsuitable for manual deconvolution. Rather than using fixed thresholds, the probabilistic approach to DNA mixture deconvolution models a variety of DNA behaviors and the uncertainty that they entail.[132]

With each PGS run, the software generates diagnostic values. Although the specific diagnostics may vary depending on the program used, the intent is to aid in determining how well the software was able to explain the profile given the underlying models and assumptions.[133] These diagnostics can include mixture proportions, estimated template amount of DNA, statistical weights assigned to different possible genotype sets, and LRs for individual loci.

In addition, some systems provide "secondary diagnostics" that relate to the purely technical performance of the system. These may include a log-likelihood statistic that provides an overall

[130] Coble MD, Bright JA. Probabilistic Genotyping Software: An Overview. *Forensic Science International: Genetics*. 2019; 38:219-24. doi:10.1016/j.fsigen.2018.11.009.

[131] STRmix™. Live Labs. Accessed April 24, 2024. https://strmix.com/strmix/live-strmix-labs/; United States Government Accountability Office (GAO). *Science & Tech Spotlight: Probabilistic Genotyping Software*. Vol. GAO-19-707SP. 2019. https://www.gao.gov/assets/gao-19-707sp.pdf. In 2021, John Buckleton reported that STRmix™ is used by roughly 80% of the FSSPs using PGS within the United States. Discussions on PGS within this report therefore reflect the current landscape of PGS use in the United States.

[132] Moretti TR, Just RS, Kehl SC, Willis LE, Buckleton J, Bright JA, Taylor DA, Onorato AJ. Internal Validation of STRmix™ for the Interpretation of Single Source and Mixed DNA Profiles. *Forensic Science International: Genetics*. 2017; 29:126-144. doi:10.1016/j.fsigen.2017.04.004.

[133] Russell L, Cooper S, Wivell R, Kerr Z, Taylor D, Buckleton J, Bright JA. A Guide to Results and Diagnostics within a STRmix™ Report. *WIREs Forensic Science*. 2019; 1(6):e1354. doi:10.1002/wfs2.1354.

measure of the goodness-of-fit of the data to the fitted model (the Gelman-Rubin [GR] statistic in the case of Markov chain Monte Carlo [MCMC] approximations) and estimates of allelic and stutter variance.

Every PGS-assisted interpretation should include a review of an established set of software diagnostics. Analysts need to know what steps to take when the range of acceptable software diagnostic values is exceeded (e.g., rerunning with different software settings). The output of a PGS run should be consistent with the EPG as assessed by the analyst. For example, a two-person mixture profile with a 1:1 mixture ratio should produce a PGS result that corresponds to the allelic pattern the analyst observes on the EPG. In this sense, the analyst's training, knowledge, and experience are needed to properly vet the software's interpretation. This assessment may also serve to verify that the input file, which is often manually provided to the software by the user, was correct. The evaluation is inherently more challenging when the profile is complex (e.g., a four-person mixture of equal proportions displaying drop-out).

PGS models various uncertainties, and the diagnostics reflect the space between the expected (i.e., modeled) and the observed (i.e., the input EPG). The larger the gap, the further such diagnostics will be from the empirically established and validated norms. For example, if an initial NOC is underestimated, the software will need to explain additional allelic contributions by either accepting higher-than-expected stutter or by considering the drop-in of alleles, or both. When possible and allowed by the interpretation software, the extent to which such variances are encountered is reflected in the *primary* and *secondary diagnostics*. In reviewing the diagnostics, analysts are assessing for "intuitiveness" and determining if the diagnostics meet "qualitative expectations."[134] Based on this review, the analyst will decide whether to accept the results or reinterpret the profile under different software settings or different assumptions.

Primary diagnostics may be thought of as a component of profile characterization in general. Analysts have been evaluating many of these factors since the early days of DNA STR typing. These factors include mixture proportions, possible genotype combinations, and whether the statistical calculation is consistent with the observed profile (e.g., the POI is *excluded* when the evidence and reference profiles do not share allelic similarities). Software programs that assign weights to allowable genotype combinations may indicate which combinations better explain the evidence.[135] Alternatively, genotype combinations may be assigned relative ratios wherein the larger the ratio, the greater the confidence in the given genotype.[136] Genotype weights, or ratios,

[134] Ibid.

[135] Bright JA, Taylor D, McGovern C, Cooper S, Russell L, Abarno D, Buckleton J. Developmental Validation of STRmix™, Expert Software for the Interpretation of Forensic DNA Profiles. *Forensic Science International: Genetics*. 2016; 23:226-39. doi:10.1016/j.fsigen.2016.05.007.

[136] Gill P, Benschop C, Buckleton J, Bleka O, Taylor D. A Review of Probabilistic Genotyping Systems: EuroForMix, DNAStatistX and STRMix™. *Genes (Basel)*. 2021; 12(10):1559. doi:10.3390/genes12101559.

may then be incorporated into subsequent LR calculations. The benefit of primary diagnostics is that they may be cross-referenced to the observed EPG of a given profile to evaluate the output against the expectations of the genotype weights for each contributor (i.e., modeling of drop-in, drop-out, stutter versus allelic, and mixture ratios).

Secondary diagnostics are a newer concept for DNA analysts and are typically harder to assess than primary diagnostics.[137] Depending on the PGS, these diagnostics may include the GR and the variability in allele and stutter peak heights (expected versus observed peak heights). The GR reflects the performance of the MCMC algorithm for a given run, meaning how well the independent chains converged and whether the software was able to find acceptable explanations for the forensic profile.[138] The allele and stutter peak height variances are established during an FSSP's internal validation using single-source profiles. The difficulty with such diagnostics is establishing the acceptable range.

Regardless of the diagnostic outputs, the analyst should still review the deconvolution results. These values are intended to be used as a guide and may indicate one or more of the following: stochastic variation present within a profile, incorrect modeling of stutter as an allele (or an allele as stutter), peak height imbalances due to relatedness and the sharing of alleles, or an incorrect NOC.[139] An FSSP's internal validation will establish the functional limit of a particular system within their workflow (e.g., only amplify samples above an established quantitation threshold or only interpret profiles with four or fewer contributors). However, when analyzing casework profiles within the validated range, the analyst may need to decide whether to accept or reject the interpretation based on the run diagnostics.

SOPs should establish how far out of range a given diagnostic may be for the interpretation to be acceptable. Training, experience, and thorough SOPs are crucial to providing the analyst with the appropriate tools to make this determination. If a profile is deemed suitable for interpretation despite exhibiting out-of-range diagnostics, the justification must be documented (e.g., the profile appears degraded, the assumed presence of first-order relatives is influencing peak height ratios across multiple loci).

If accepting a result with an out-of-range diagnostic, all reasonable attempts should be made to determine the cause and to ensure the interpretation is not adversely affected. For example, if elevated stutter variance is observed, the analyst should verify that improbable genotypes are not being accepted (e.g., modeling a stutter allele as allelic or vice versa). In some cases, it may

[137] Russell L, Cooper S, Wivell R, Kerr Z, Taylor D, Buckleton J, Bright JA. A Guide to Results and Diagnostics within a STRmix™ Report. *WIREs Forensic Science*. 2019; 1(6):e1354. doi:10.1002/wfs2.1354.

[138] Buckleton J, Bright JA, Taylor D. *Forensic DNA Evidence Interpretation*. 2nd ed. CRC Press: Boca Raton, 2016. doi:10.4324/9781315371115.

[139] Duke K, Myers S, Cuenca D, Wallin J. Improving the Utilization of STRmix™ Variance Parameters as Semi-Quantitative Profile Modeling Metrics. *Genes (Basel)*. 2022; 14(1):102. doi:10.3390/genes14010102. see also STRmix™ User's Manuals.

not be possible to identify a clear cause. Inter- and intra-FSSP variation may exist when it comes to accepting or rejecting an interpretation. If additional PGS runs are performed in response to the initial out-of-range diagnostics, all data should be retained and provided to interested parties if requested, even if the profile is ultimately deemed uninterpretable.

Recommendation 3.7: Forensic science service providers should validate and apply interpretation methods that take into account all data necessary to help address the propositions. Currently, for the interpretation of DNA comparisons, continuous probabilistic genotyping is the only interpretation technique that meets this criterion.

The suitability and complexity issues highlighted are not new to DNA mixture interpretation. However, with PGS, analysts can interpret a greater number of complex mixture profiles. PGS output data and diagnostics may further assist the analyst in determining when a profile is being poorly modeled and should be considered too complex.

Recommendation 3.8: Forensic science service providers' standard operating procedures should provide criteria for assessing and documenting when a probabilistic genotyping interpretation should be rejected.

3.4.9.3 Human Factors Influencing the Interpretation of PGS Outputs

Depending on an FSSP's policy, certain system diagnostics may not have clear thresholds to aid the analyst. Typically, the internal validation of a given PGS system will establish the acceptable range; however, there is no "right" value. From a human factors perspective, key questions are:

- What factors play into the acceptance or rejection of software-assisted profile interpretations?
- Are analysts more likely to accept a PGS interpretation with an out-of-range diagnostic for complex mixture profiles, where the anticipated genotype combinations may be harder to intuit, simply because they have no other means by which to interpret such a profile?
- How do other factors such as significant case backlogs, short turnaround-time expectations, or high-profile cases influence this decision?

Analysts should recognize when PGS has incorrectly modeled the input profile data and intervene accordingly. For example, an elevated stutter peak may be mismodeled as allelic, causing incorrect genotype combinations to be accepted. Or an unresolved and unlabeled allelic peak may be visible as a shoulder of another called allele on an EPG. Upon comparison to a true contributor, an erroneous, single-locus LR all but indistinguishable from zero may result. Unlike

This publication is available free of charge from: https://doi.org/10.6028/NIST.IR.8503

in a validation study where the ground truth is known, false exclusions due to mismodeling may be harder to detect in casework.

Other nonintuitive results may occur when the mixture proportions are incorrectly modeled. A mixture of two individuals with one trace contributor may be characterized as 50:50 when it is really 99:1. In some instances, certain diagnostics may or may not exceed the acceptable range. The analyst should compare the PGS output to the corresponding EPG, evaluate the deconvolved genotype weights, and determine if the software result aligns with the profile. The analyst may need to inform the software of the expected mixture proportions. On the other hand, mismodeling may be caused by the human misinforming the software (e.g., inputting the incorrect NOC or leaving in an artifact that is then modeled as allelic). In these instances, the software is limited by the human's performance. As such, understanding when human expertise may be needed to assist technology is essential.

Analysts should not be passive participants in PGS-assisted interpretations. Instead, tasks should be distributed between the human expert and the software to best use the strengths of both components. Emphasizing user accountability and the critical evaluation of PGS results coupled with internal validation and continued training exercises (see **Sec. *8.9*: *Provision of Practice and Feedback Opportunities for Expertise Development***) may help minimize overreliance on software. In addition, FSSPs that identify instances of overreliance should understand and appreciate what the contributing factors may have been. Time pressure, the complexity of the task, or the need for additional training may play a role.

3.4.10 Contamination Detection

The increased sensitivity of modern DNA typing methods and advances in interpretation technologies have increased the chances of detecting low-level contamination, potentially causing downstream interpretation challenges. *SWGDAM Contamination Prevention and Detection Guidelines for Forensic DNA Laboratories*[140] provides best practices and guidance for the minimization and detection of DNA contamination. Standard 9.12 of the FBI QAS requires FSSPs to establish policies and procedures to detect and minimize contamination.[141] The European Network of Forensic Science Institutes (ENFSI)[142] and OSAC[143] have published

[140] Scientific Working Group on DNA Analysis Methods (SWGDAM). *Contamination Prevention and Detection Guidelines for Forensic DNA Laboratories*. 2017. https://www.swgdam.org/_files/ugd/4344b0_c4d4dbba84f1400a98eaa2e48f2bf291.pdf.

[141] Federal Bureau of Investigation (FBI). *Quality Assurance Standards for Forensic DNA Testing Laboratories*. 2020. https://le.fbi.gov/file-repository/forensic-qas-070120.pdf/view.

[142] European Network of Forensic Science Institutes (ENFSI). *Guideline for DNA Contamination Minimization in DNA Laboratories*. 2023. https://enfsi.eu/wp-content/uploads/2023/10/ENFSI-GUIDELINE-FOR-DNA-CONTAMINATION-MINIMIZATION-IN-DNA-LABORATORIES.pdf.

[143] Organization of Scientific Area Committees (OSAC). *Standard for Interpreting, Comparing and Reporting DNA Test Results Associated with Failed Controls and Contamination Events, Version 2.0. OSAC Proposed Standard 2020-S-0004*. May 19, 2023, 2021. https://www.nist.gov/system/files/documents/2021/06/01/OSAC%202020-S-

additional guidelines addressing contamination. See ***Sec. 8.3.5.3: Contamination Prevention*** and ***Sec. 8.3.5.4: Elimination Databases*** for a more general discussion on contamination.

Most guidelines and FSSP efforts focus on creating and establishing laboratory engineering controls rather than providing strategies for contamination detection. Comparing profiles within a batch of samples to one another or performing database searches comparing evidence and personnel profiles (when possible) can detect some sample-to-sample and personnel-to-sample contamination events. However, specific examples of which tools are most effective are not provided. Some PGS provide useful options for performing these steps including database search capabilities and mixture-to-mixture comparison tools.[144]

Some FSSPs compare profiles using their data analysis software.[145] For example, GeneMapper ID-X™ has a profile comparison tool that will compare samples within a project to one another and to database profiles. Any samples with overlap above a user-set percentage are flagged for review. While this tool may be useful for the evaluation of simpler profiles (i.e., single-source or lower-order mixtures), possible overlap in alleles between higher-order mixtures is more difficult to evaluate because of allele sharing, stacking, and peak height imbalances.

Typically, FSSPs not using PGS will analyze profiles with the established stutter filters applied (i.e., stutter peaks are unlabeled on the EPG). However, for some FSSPs using PGS, data analysis occurs with the stutter filters off, meaning the analysis software will label all alleles above the set AT. Reviewing profiles with both the parent and stutter peaks labeled is challenging for most analysts when first switching to a PGS-based workflow. The number of labeled peaks for mixture profiles increases significantly when stutter filters are not applied. The presence of stutter peaks, especially in mixture profiles, may complicate the detection of contamination depending on the method used to perform a quality check on the profiles. For example, when using the GeneMapper ID-X™ profile comparison tool,[146] it may be more efficient to analyze first with the stutter filters applied, thereby removing the labeled stutter peaks, prior to assessing potential sample-to-sample contamination. This may assist the analyst in visually assessing profiles that share alleles. The presence of partial profiles may further complicate searches when using basic comparison tools. For example, a profile with only two alleles detected may be flagged any time those same alleles are also present in other profiles included in the search, which the analyst should then review.

0004_Standard_for_Interpreting_Comparing_and_Reporting_DNA_Test_Results_with_Failed_Controls_and_Contanimation%20FINAL%20OSAC%20PROPOSED.pdf.

[144] STRmix™. DBLR™. Accessed March 27, 2024. https://strmix.com/dblr.

[145] Available software includes GeneMapper ID-X™, GeneMarker®, OSIRIS, and FaSTR™.

[146] Lackey A. Tips and Tricks for Using GeneMapper ID-X Software. ThermoFisher Scientific. Accessed March 27, 2024. https://www.thermofisher.com/blog/behindthebench/tips-and-tricks-for-using-genemapper-id-x-software/.

Manual methods of contamination assessment are time consuming, cumbersome, and subject to inter- and intra-analyst variation and analyst fatigue. Detecting and assessing potential contamination becomes challenging when looking through a large number of mixture profiles. These manual methods are less effective than using software tools, and they are limited by the analyst's ability to visually recognize potential contamination (both sample-to-sample and personnel-to-sample contamination).

LR-based methods can search large databases quickly and can provide a statistical value to any DNA profile comparison. These tools can be thoroughly vetted during internal validation to establish a set contamination threshold, above which the results will be further investigated and reported (e.g., a database LR greater than 10,000 requires further evaluation by the analyst). This ensures consistency in detection and reporting and reduces the human factors involved in detecting contamination. The search results from software tools can also be maintained electronically, providing more transparency and documentation.

Depending on FSSP policy and the level of contamination observed, the analysis will be repeated (if possible) or the DNA TL may consider whether to use the data for analysis. Consideration should be given to the degree of the contamination, the performance of the control samples, and if the cause of the contamination can be determined. It is good practice to monitor the number and frequency of drop-in alleles in negative control samples. Some FSSPs may condition the interpretation on the contaminating profile, when possible, thereby allowing the remaining components of the profile to be interpreted. At a minimum, if contamination is detected, the report should indicate so and should state whether the profile was used for interpretation.

3.5 Comparison Phase

Regardless of the method of comparison (e.g., manual or probabilistic), FSSPs should follow the following three principles of interpretation:[147]

1. Relevant case information should be used in formulating the issues that forensic DNA analysis can provide insight to.[148]

[147] European Network of Forensic Science Institutes (ENFSI). *ENFSI Guideline for Evaluative Reporting in Forensic Science: Strengthening the Evaluation of Forensic Results across Europe (STEOFRAE), Version 3.0*. 2015. https://enfsi.eu/wp-content/uploads/2016/09/m1_guideline.pdf; Evett IW, Jackson G, Lambert JA, McCrossan S. The Impact of the Principles of Evidence Interpretation on the Structure and Content of Statements. *Science & Justice*. 2000; 40(4):233-9. doi:10.1016/S1355-0306(00)71993-9; Evett IW, Weir BS. *Interpreting DNA Evidence: Statistical Genetics for Forensic Scientists*. Sinauer Associates Inc,: Sunderland, MA, 1998. ; Hicks T, Buckleton J, Castella V, Evett IW, Jackson G. A Logical Framework for Forensic DNA Interpretation. *Genes (Basel)*. 2022; 13(6):957. doi:10.3390/genes13060957; Jackson G. The Scientist and the Scales of Justice. *Science & Justice*. 2000; 40(2):81-5. doi:10.1016/S1355-0306(00)71947-2; Jackson G, Jones S, Booth G, Champod C, Evett IW. The Nature of Forensic Science Opinion - a Possible Framework to Guide Thinking and Practice in Investigations and in Court Proceedings. *Science & Justice*. 2006; 46(1):33-44. doi:10.1016/s1355-0306(06)71565-9.

[148] The information considered can impact the value of the findings and if the information changes—or is incorrect—then a new evaluation will be needed. Furthermore, the information that the DNA analyst knows or assumes should be included in the report. The factfinder should assess the results in the context of all other evidence in a case.

2. To be balanced, the analyst should consider at least two mutually exclusive propositions when assessing the value of biological results.
3. Analysts should assign the probability of the findings, not the probability of the (alleged) facts (see **Callout Box 6.3**).

By following these principles, the comparison should be logical, balanced, robust, and transparent.

3.5.1 Comparison Without a POI

If a profile is suitable for interpretation, but there is no POI, steps can be taken to inform subsequent investigative decisions such as what additional testing or comparisons may be useful. Depending on the FSSP, or at the discretion of the analyst, comparisons may be made between forensic profiles within or between cases. Profile-to-profile comparisons may be prone to bias and similar influences as those that occur in comparisons to a POI (see ***Sec. 3.5.3*: *Comparison to a POI***). The discussions in this chapter focus primarily on evidence-to-known comparisons. In the absence of POI reference samples, an analyst may be able to:

- Provide possible explanations for the observed findings (see ***Sec. 5.3.2.4*: *Possible Explanations for DNA Results***). Explanations are for investigative purposes only and are different from comparisons performed using the principles of interpretation.
- Upload the profile to a database and potentially provide investigative leads (see ***Sec. 5.3.2.2*: *Investigative Leads Produced Following DNA Database Searches***).
- Suggest additional testing strategies such as analysis of additional evidence items or alternate technologies (e.g., Y-STRs or SNP analysis for Forensic Investigative Genetic Genealogy [FIGG]).

3.5.2 Database Comparisons

One of the primary ways that DNA analysis can assist with answering *who* questions when no POI has been developed is through entry, upload, and search in a DNA database. The primary tool that FSSPs throughout the United States use is the Combined DNA Index System (CODIS),[149] which was designed to compare a target DNA record against the DNA records contained in a CODIS database. One component of CODIS is the National DNA Index System (NDIS), which contains DNA records on the national level that have been contributed by federal, state, and local participating FSSPs.

[149] Federal Bureau of Investigation (FBI). Frequently Asked Questions on CODIS and NDIS. Accessed March 27, 2024. https://www.fbi.gov/how-we-can-help-you/dna-fingerprint-act-of-2005-expungement-policy/codis-and-ndis-fact-sheet.

This publication is available free of charge from: https://doi.org/10.6028/NIST.IR.8503

The *NDIS Operational Procedures*[150] provide guidance on the eligibility of entry and upload of profiles into NDIS. NDIS requires compliance with the FBI QAS and accreditation standards. These procedures do not provide specific guidance for profile interpretation for the purposes of developing a CODIS entry. This creates the opportunity for variability between and within FSSPs to decide how to enter a profile (or a partial profile). For example, while an FSSP may have implemented PGS as a more objective way to perform deconvolutions and comparisons, the FSSP has the flexibility to modify or tailor the resulting component breakdowns for the purposes of developing a CODIS entry.

These decisions can impact the software's ability to return a candidate match as well as the analyst's ability to discern if the candidate match is a possible investigative lead. Additionally, not all FSSPs using PGS employ an LR-based approach for assessing the value of a candidate match in CODIS. This step may still be performed manually. Finally, governmental FSSPs often rely heavily on private FSSPs to help tackle their caseloads. Private FSSPs, however, do not have CODIS access. Instead, government FSSPs review the results, take ownership, and enter the profiles. This results in interpretations of data generated outside of the government FSSP system and requires procedures specific for the review of outsourced data for the purposes of CODIS entry. These procedures may differ from the FSSP's procedures for internal data review.[151]

3.5.3 Comparison to a POI

If the profile is suitable for comparison and there is a POI profile available, the analyst will compare the forensic profile to the POI profile. This comparison will be based on an evaluation given at least one set of mutually exclusive propositions. Propositions are not unique to FSSPs using PGS. A relatively common example of a pair of propositions is (1) the POI is the source of the DNA (first proposition), and (2) an unknown individual is the source of the DNA (second proposition).

The Expert Working Group (EWG) believes that LRs are the most effective and efficient way for analysts to assess and communicate the value of the findings (see ***Sec. 4.3*: *The Likelihood Ratio***). However, FSSPs may have different resources, approaches, and methods. Alternative methods for expressing the value of DNA comparisons are discussed in greater detail in ***Sec. 4.4*: *Other Quantitative Expressions of DNA Results***.

[150] Federal Bureau of Investigation (FBI). *Quality Assurance Standards for Forensic DNA Testing Laboratories*. 2020. https://le.fbi.gov/file-repository/forensic-qas-070120.pdf/view; Federal Bureau of Investigation (FBI) Laboratory. *National DNA Index System (NDIS) Operational Procedures Manual, Version 4*. 2016. https://ucr.fbi.gov/lab/biometric-analysis/codis/ndis-procedures-manual.

[151] Federal Bureau of Investigation (FBI). *Quality Assurance Standards for Forensic DNA Testing Laboratories*. 2020. https://le.fbi.gov/file-repository/forensic-qas-070120.pdf/view.

3.5.3.1 Formulating Propositions in an LR Framework

Propositions are key to evaluating findings in accordance with the principles of interpretation.[152] Once the analyst has defined the relevant issue(s) based on the case circumstances, they can start to formulate propositions to assess the findings. Propositions and proposition pairs should have the following properties:

1. They should be based on the available case information.
2. They should be mutually exclusive (i.e., they cannot both be true simultaneously).
3. Although not necessarily exhaustive, they should cover all reasonable options dictated by the case circumstances and any other relevant known background. This means that multiple sets of propositions may be needed to properly evaluate the findings.
4. They should be explicit and leave no doubt about what is being proposed.
5. They should be structured so as not to transpose the conditional (see **Sec. *6.12.1*: *Properly Explaining the Quantitative Value of the Results***).

Propositions are first informed by the provided case information and later updated based on the data that is developed. Propositions should be set prior to any comparison to a POI's DNA. Importantly, the data may not support the initial propositions that were identified (e.g., lack of data to support the expectation of an individual's DNA on an intimate item). While in general, propositions should be set prior to the comparison phase, in some instances, comparisons can result in the formulation of additional propositions, such as when samples from multiple POIs have been submitted.

Upon performing the comparisons and using propositions considering each POI separately, the analyst may determine that the data support proposition(s) about multiple POIs.[153] There may

[152] Evett IW, Jackson G, Lambert JA, McCrossan S. The Impact of the Principles of Evidence Interpretation on the Structure and Content of Statements. *Science & Justice*. 2000; 40(4):233-9. doi:10.1016/S1355-0306(00)71993-9; Jackson G, Jones S, Booth G, Champod C, Evett IW. The Nature of Forensic Science Opinion - a Possible Framework to Guide Thinking and Practice in Investigations and in Court Proceedings. *Science & Justice*. 2006; 46(1):33-44. doi:10.1016/s1355-0306(06)71565-9.

[153] Buckleton J, Bright JA, Taylor D, Evett I, Hicks T, Jackson G, Curran JM. Helping Formulate Propositions in Forensic DNA Analysis. *Science & Justice*. 2014; 54(4):258-61. doi:10.1016/j.scijus.2014.02.007; Buckleton J, Taylor D, Bright JA, Hicks T, Curran JM. When Evaluating DNA Evidence within a Likelihood Ratio Framework, Should the Propositions Be Exhaustive? *Forensic Science International: Genetics*. 2021; 50:102406. doi:10.1016/j.fsigen.2020.102406; Cook R, Evett IW, Jackson G, Jones PJ, Lambert JA. A Hierarchy of Propositions: Deciding Which Level to Address in Casework. *Science & Justice*. 1998; 38(4):231-9. doi:10.1016/S1355-0306(98)72117-3; Evett IW, Jackson G, Lambert JA. More on the Hierarchy of Propositions: Exploring the Distinction between Explanations and Propositions. *Science & Justice*. 2000; 40(1):3-10. doi:10.1016/S1355-0306(00)71926-5; Evett IW, Jackson G, Lambert JA, McCrossan S. The Impact of the Principles of Evidence Interpretation on the Structure and Content of Statements. *Science & Justice*. 2000; 40(4):233-9. doi:10.1016/S1355-0306(00)71993-9; Gill P, Hicks T, Butler JM, Connolly E, Gusmao L, Kokshoorn B, Morling N, van Oorschot RAH, Parson W, Prinz M, Schneider PM, Sijen T, Taylor D. DNA Commission of the International Society for Forensic Genetics: Assessing the Value of Forensic Biological Evidence - Guidelines Highlighting the Importance of Propositions: Part I: Evaluation of DNA Profiling Comparisons Given (Sub-) Source Propositions. *Forensic Science International: Genetics*. 2018; 36:189-202. doi:10.1016/j.fsigen.2018.07.003; Gittelson S, Kalafut T, Myers S, Taylor D, Hicks T, Taroni F, Evett IW, Bright JA, Buckleton J. A Practical Guide for the Formulation of Propositions in the Bayesian Approach to DNA Evidence Interpretation in an Adversarial Environment. *Journal of Forensic Sciences*. 2016; 61(1):186-95. doi:10.1111/1556-4029.12907; Hicks T, Biedermann A, de Koeijer JA, Taroni F, Champod C, Evett IW. The Importance of Distinguishing Information from Evidence/Observations When Formulating Propositions. *Science & Justice*. 2015; 55(6):520-5. doi:10.1016/j.scijus.2015.06.008; Hicks T, Buckleton J, Castella V, Evett IW, Jackson G. A Logical Framework for Forensic DNA Interpretation. *Genes (Basel)*. 2022; 13(6):957. doi:10.3390/genes13060957; Taylor D, Volgin L, Kokshoorn B, Champod C. The Importance of Considering Common Sources of Unknown DNA When Evaluating Findings Given Activity Level Propositions. *Forensic Science International: Genetics*. 2021; 53:102518. doi:10.1016/j.fsigen.2021.102518.

also be instances where, upon comparison, the analyst discovers features in the profile that are indicative of relatedness. This discovery may prompt additional case information and the consideration of alternate propositions. See **Callout Box 3.5** and **Callout Box 3.6** for additional discussions regarding the formulation of propositions.

Callout Box 3.5: Example Propositions Based on Relevant Contextual Case Information

Case scenario #1: The complainant (C) reported returning to their apartment to find it had been burglarized. Money had been stolen from the top drawer of their dresser. The drawer pull was swabbed for DNA. C lived alone and provided an elimination buccal swab. DNA analysis produced a three-person mixture of which C was an assumed contributor. A POI buccal swab was submitted for comparisons.

Based on this case information, the propositions are:

H_1: The DNA mixture is from C, the POI, and one unknown individual.
H_2: The DNA mixture is from C and two unknown individuals.

Case scenario #2: The complainant (C) was found with multiple stab wounds outside of the apartment building. CCTV footage showed an individual running from the building and discarding an object. A suspect (POI) was later apprehended. A knife was found along the flight path and was submitted for serological and DNA testing along with known samples from C and the POI. The blade of the knife tested positive for the possible presence of blood and was swabbed for DNA yielding a two-person mixture.

Based on this case information, the propositions could be:

H_1: The DNA mixture is from the POI and one unknown individual.
H_2: The DNA mixture is from two unknown individuals.

And

H_1: The DNA mixture is from C and one unknown individual.
H_2: The DNA mixture is from two unknown individuals.

A third pair of propositions also may be considered:

H_1: The DNA mixture is from C1 and the POI.
H_2: The DNA mixture consists of two unknown individuals.

However, this pair could lead to a much larger LR than those for the two previous proposition pairs. If the individual contributor LR values are many orders of magnitude apart, this last proposition pair can potentially mislead the end-user.

For a more in-depth discussion of additional proposition pairs, see Hicks et al., 2022 and Hicks et al., 2021.[154]

[154] Hicks T, Buckleton J, Castella V, Evett IW, Jackson G. A Logical Framework for Forensic DNA Interpretation. *Genes (Basel)*. 2022; 13(6):957. doi:10.3390/genes13060957; Hicks T, Kerr Z, Pugh S, Bright JA, Curran JM, Taylor D, Buckleton J. Comparing Multiple POI to DNA Mixtures. *Forensic Science International: Genetics*. 2021; 52:102481. doi:10.1016/j.fsigen.2021.102481.

3.5.4 Considering Relatives

When assuming that contributors to a mixture are *unrelated*, PGS has shown powerful discrimination in separating true donors from non-donors in a wide range of samples.[155] However, analysts should remember that the same power may not be present with mixtures of *related* individuals. Non-contributors who are relatives of true contributors can produce high LRs when considering propositions such as (1) the POI and two unknown individuals are the source of the DNA mixture, or (2) three unknown individuals are. For example, a study conducted by Kalafut et al. showed that six non-contributors, who were relatives of the true donors in a two-person mixture, produced LRs ranging from 740 million (7.4×10^8) to 4.07 trillion (4.07×10^{12}) when run without conditioning, at times yielding a higher LR than the true minor donor.[156]

Because of how DNA is transmitted from parents to children, first-degree relatives will share many alleles. As such, generally, relatives of a true contributor may have an LR larger than is typical of unrelated individuals when considering propositions such as the POI and two unknown individuals being the sources of the DNA mixture, as opposed to three unknown individuals being the sources. Because siblings share, on average, half of their DNA, Kelly et al. have suggested that LRs larger than 1 are the "correct" or "expected" result.[157]

As outlined in the *ENFSI Guideline on Evaluative Reporting*, "the use of a likelihood ratio does not generally imply that one of the two propositions considered must be true. Though the considered propositions are those deemed most relevant, they do not need to be exhaustive, so both propositions could be false. The likelihood ratio says nothing about propositions other than the two that were considered."[158] This is one reason why it is essential to be clear that, should the propositions or case information change, the value of the findings will also change. Furthermore, low-level DNA mixtures with allelic drop-out heighten the risk of large LRs for non-contributor relatives.[159]

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[155] Buckleton J, Bright JA, Gittelson S, Moretti TR, Onorato AJ, Bieber FR, Budowle B, Taylor DA. The Probabilistic Genotyping Software STRmix: Utility and Evidence for Its Validity. *Journal of Forensic Sciences*. 2019; 64(2):393-405. doi:10.1111/1556-4029.13898; Kelly H, Bright JA, Kruijver M, Cooper S, Taylor D, Duke K, Strong M, Beamer V, Buettner C, Buckleton J. A Sensitivity Analysis to Determine the Robustness of STRmix with Respect to Laboratory Calibration. *Forensic Science International: Genetics*. 2018; 35:113-22. doi:10.1016/j.fsigen.2018.04.009; Noël S, Noël J, Granger D, Lefebvre JF, Seguin D. STRmix™ Put to the Test: 300 000 Non-Contributor Profiles Compared to Four-Contributor DNA Mixtures and the Impact of Replicates. *Forensic Science International: Genetics*. 2019; 41:24-31. doi:10.1016/j.fsigen.2019.03.017; Schuerman C, Kalafut T, Buchanan C, Sutton J, Bright JA. Using the Nondonor Distribution to Improve Communication and Inform Decision Making for Low LRs from Minor Contributors in Mixed DNA Profiles. *Journal of Forensic Sciences*. 2020; 65(4):1072-84. doi:10.1111/1556-4029.14306.

[156] Kalafut T, Pugh S, Gill P, Abbas S, Semaan M, Mansour I, Curran JM, Bright JA, Hicks T, Wivell R, Buckleton J. A Mixed DNA Profile Controversy Revisited. *Journal of Forensic Sciences*. 2022; 67(1):128-35. doi:10.1111/1556-4029.14912.

[157] Kelly H, Coble M, Kruijver M, Wivell R, Bright JA. Exploring Likelihood Ratios Assigned for Siblings of the True Mixture Contributor as an Alternate Contributor. *Journal of Forensic Sciences*. 2022; 67(3):1167-75. doi:10.1111/1556-4029.15020.

[158] European Network of Forensic Science Institutes (ENFSI). *ENFSI Guideline for Evaluative Reporting in Forensic Science: Strengthening the Evaluation of Forensic Results across Europe (STEOFRAE), Version 3.0*. 2015. https://enfsi.eu/wp-content/uploads/2016/09/m1_guideline.pdf.

[159] Kelly H, Coble M, Kruijver M, Wivell R, Bright JA. Exploring Likelihood Ratios Assigned for Siblings of the True Mixture Contributor as an Alternate Contributor. *Journal of Forensic Sciences*. 2022; 67(3):1167-75. doi:10.1111/1556-4029.15020.

Even if expected, a large LR for any non-contributor, relative or not, has the potential to adversely impact the judicial process. Analysts should be aware when formulating propositions without conditioning or considering relatives that the probability of a high LR for a non-contributing relative is more common than for an unknown, unrelated individual. A similar outcome is of course also true for Random Man Not Excluded (RMNE), **Random Match Probability (RMP)**, or any calculations involving a DNA comparison and first-degree relatives.

The problem of relatedness precedes and is not unique to PGS.[160] Analysts and the FSSP's case management system should make every effort to find out when relatives are the possible alternate sources of DNA so that this information may be appropriately factored into propositions. **Callout Box 3.6** presents strategies for situations where a relative of the POI is a possible contributor to the DNA. Some of these strategies also apply to FSSPs that do not yet use PGS.

Callout Box 3.6: Strategies for Situations Where Relatives of the POI Are Possible Contributors

1. **Attention to case conditions:** Common fact patterns that increase the relatedness risk should trigger additional information gathering from an FSSP's case management systems and analysts. For example, when firearms are recovered in a search of a family home, relevant questions include: How many first-order relatives (both adults and children) have regular access to the home? Were any other individuals—related or not—present when the items were recovered? Can reference samples from any of these individuals be obtained? Likewise, when DNA is recovered from bedding or clothing in a familial sexual assault case, relevant questions include: How many first-order relatives (both adults and children) live or have regular access to the home? Are the items commingled in the laundry along with those of other family members? Can reference samples from the family members be obtained?
2. **Conditioning when profiles are available:** One suggested strategy is to condition upon available profiles.[161] In one study, non-contributors were excluded when using peak height information and conditioning.[162] Accordingly, "maximum effort should be made by the investigating body to obtain references from the relatives suspected of involvement. This will either allow elimination or their use as conditioning profiles."[163] However, conditioning alone has its limitations and may be better paired with additional strategies such as the use of "mixture priors." STRmix™ developers conducted a study of a mother-father-child mixture and concluded that the only "reasonable results" were obtained from using a feature called Informed Mixture Proportion Priors (IMPP)—where the analyst inputs an assumed mixture ratio before the deconvolution—while conditioning on a known sample.[164] In another study, the use of the IMPP feature, along

[160] Kalafut T, Bright JA, Taylor D, Buckleton J. Investigation into the Effect of Mixtures Comprising Related People on Non-Donor Likelihood Ratios, and Potential Practises to Mitigate Providing Misleading Opinions. *Forensic Science International: Genetics*. 2022; 59:102691. doi:10.1016/j.fsigen.2022.102691.

[161] Kalafut T, Pugh S, Gill P, Abbas S, Semaan M, Mansour I, Curran JM, Bright JA, Hicks T, Wivell R, Buckleton J. A Mixed DNA Profile Controversy Revisited. *Journal of Forensic Sciences*. 2022; 67(1):128-35. doi:10.1111/1556-4029.14912.

[162] Ibid.

[163] Kalafut T, Bright JA, Taylor D, Buckleton J. Investigation into the Effect of Mixtures Comprising Related People on Non-Donor Likelihood Ratios, and Potential Practises to Mitigate Providing Misleading Opinions. *Forensic Science International: Genetics*. 2022; 59:102691. doi:10.1016/j.fsigen.2022.102691.

[164] Lin M-H, Bright JA, Pugh SN, Buckleton J. The Interpretation of Mixed DNA Profiles from a Mother, Father, and Child Trio. *Forensic Science International: Genetics*. 2020; 44:102175. doi:10.1016/j.fsigen.2019.102175.

with conditioning in STRmix™, was also shown to be more effective than unconditioned use of STRmix™ (or conditioning alone) when comparing non-contributing relatives in a DNA mixture.[165]

In an internal validation of STRmix at the Los Angeles County Sheriff's Department, a "subset of the two and three-person relative mixture samples was analyzed under alternate conditioning hypotheses."[166] Alternative scenarios included conditioning upon the presence of one parent in the mixture when comparing an offspring, or conditioning upon both parents being present in the mixture when comparing an offspring. As a result, the Los Angeles County Sheriff's Department reported that while conditioning generally increases the LR for Hp [H_1] true experiments, the mixture proportions of one sample was inconsistent with qualitative expectations.[167] Mixture proportions for that sample improved only after using IMPP.[168] However, the use of mixture priors to improve the distinction between true contributors and their related non-contributors may not be a practical suggestion, as it requires information the analyst does not, or cannot, know. This is an important limitation to consider and convey when an FSSP employs this process. Additionally, when allele sharing is minimal, analysts may have only a few loci with which to assess mixture ratios. Analysts should take these limitations of conditioning into account when conveying the value of the evidence to end-users.

3. **Consider alternative meaningful propositions:** When elimination samples are not available, the analyst should seek additional case information on who could be an alternate source of the DNA and carefully consider the resulting propositions. If meaningful to the case, the alternative should involve a relative and not just an unknown, unrelated individual. The analyst should also consider whether human intervention into the deconvolution—in the form of mixture priors or other PGS tool—is warranted.[169] The analyst should also remember that compound propositions can be used; for example, running two related individuals in H_1 might result in a very low LR, even though individually they produce high LRs.[170] Finally, PGS-calculated LRs may automatically include alternative propositions in every LR. Kelly et al. suggest using the Sibling LR, or alternative propositions considering unavailable relatives of different degrees, as a basis for further investigation, particularly "where an LR of around 1 is obtained (or an LR result which strongly supported the proposition that an unavailable sibling, rather than the POI, is a contributor to the DNA mixture)."[171] These strategies require a commitment of the FSSP during validation to ensure analysts have these tools, methods, and protocols at their disposal, and the strategies should be fully documented as well as the tools, methods, and protocols.
4. **Continued research on technologies that are more effective with mixtures:** Research has been underway to physically separate individual cells from mixtures prior to performing DNA typing to obtain single-source profiles from contributors. One study used PGS to analyze original mixtures of two to six contributors, compared to single-source sub-samples and two-cell mini-mixture sub-

[165] Kalafut T, Bright JA, Taylor D, Buckleton J. Investigation into the Effect of Mixtures Comprising Related People on Non-Donor Likelihood Ratios, and Potential Practises to Mitigate Providing Misleading Opinions. *Forensic Science International: Genetics*. 2022; 59:102691. doi:10.1016/j.fsigen.2022.102691.

[166] Brooklyn Defender Services. The Kinship Problem. Accessed March 27, 2024. https://indefenseof.us/issues/kinship-problem.

[167] Ibid.

[168] Kalafut T, Bright JA, Taylor D, Buckleton J. Investigation into the Effect of Mixtures Comprising Related People on Non-Donor Likelihood Ratios, and Potential Practises to Mitigate Providing Misleading Opinions. *Forensic Science International: Genetics*. 2022; 59:102691. doi:10.1016/j.fsigen.2022.102691.

[169] Ibid.

[170] Kelly H, Coble M, Kruijver M, Wivell R, Bright JA. Exploring Likelihood Ratios Assigned for Siblings of the True Mixture Contributor as an Alternate Contributor. *Journal of Forensic Sciences*. 2022; 67(3):1167-75. doi:10.1111/1556-4029.15020.

[171] Ibid.; Slooten K. The Comparison of DNA Mixture Profiles with Multiple Persons of Interest. *Forensic Science International: Genetics*. 2022; 56:102592. doi:10.1016/j.fsigen.2021.102592.

samples, with success in differentiating potentially related individuals.[172] The forensic DNA practitioner community should continue to partner and collaborate with the forensic DNA research community on technologies and techniques that facilitate interpretations of complex mixtures that include related individuals.

3.5.5 *Visual Versus Technology-Assisted Comparisons*

FSSPs using manual methods for deconvolution rely on a visual assessment of the similarities between a POI and forensic profile as the basis for the comparison results. FSSPs can perform the comparison using PGS software; however, some still employ a visual comparison step. This step may limit the use of PGS for deconvolution if a visual comparison results in an exclusion. At times, the visual comparison conclusion made by the analyst may conflict with the quantitative conclusion of the software. These discrepancies between the analyst and the software can make the communication of these results more challenging and confusing or even misleading (see ***Sec. 5.5.5: Propositions, DNA Comparison Statements, and Statistical Analyses***).

Regardless of the methodology for the comparisons, FSSPs should require clear documentation of the genotypes prior to any comparisons being performed. This documentation can be accomplished with a mixture deconvolution worksheet, markings on an EPG, or PGS output. Any changes to these initial determinations made during or after a comparison should also be clearly indicated (see ***Sec. 3.6: Post-Comparison Interpretation: Modifying an Interpretation After a Comparison***).

FSSPs should evaluate their processes to ensure they are transparent and prevent analysts from consciously or unconsciously adjusting their initial determinations during a comparison without a clear record of doing so. For example, electronic worksheets could incorporate audit trails that track the sequence of the mixture deconvolution, including any changes made in the process. Strategies to mitigate the cross-contamination of known and evidence samples are commonplace in the wet laboratory, and the same concept should be carefully applied to the interpretive process.

3.6 Post-Comparison Interpretation: Modifying an Interpretation After a Comparison

In casework, the ground truth is not known. However, ground truth is known during validation and research studies. These studies provide empirical data that can be applied to casework.[173] It

[172] Duffy KR, Lun DS, Mulcahy MM, O'Donnell L, Sheth N, Grgicak CM. Evidentiary Evaluation of Single Cells Renders Highly Informative Forensic Comparisons across Multifarious Admixtures. *Forensic Science International: Genetics*. 2023; 64:102852. doi:10.1016/j.fsigen.2023.102852; Huffman K, Hanson E, Ballantyne J. Probabilistic Genotyping of Single Cell Replicates from Complex DNA Mixtures Recovers Higher Contributor LRs Than Standard Analysis. *Science & Justice*. 2022; 62(2):156-63. doi:10.1016/j.scijus.2022.01.003.

[173] Taylor D, Buckleton J, Bright JA. Factors Affecting Peak Height Variability for Short Tandem Repeat Data. *Forensic Science International: Genetics*. 2016; 21:126-33. doi:10.1016/j.fsigen.2015.12.009.

is known that amplification variation may influence peak heights. Moreover, the influence on CE performance[174] may lead to poorly resolved peaks (e.g., two alleles that are one base pair apart may not be fully resolved during data analysis). These issues are not always obvious during the interpretation of casework profiles.

Another source of uncertainty is the assignment of NOC, particularly in mixtures of three or more contributors or when the contributions of individuals are not easily resolvable (i.e., equal contributions from each donor to a mixture). For example, the under-assignment of NOC may force the allele-pairing of two trace contributors, creating a composite genotype. When this produces a genotype that is not represented in either POI's reference profile, the LR at that locus will be less than 1.

These issues may not be obvious to the analyst until after comparison to the POI's reference profile. At times, it will be necessary to reinterpret a profile after looking at a given POI reference profile. For example, a single-locus LR may vary significantly from the remaining per-locus LRs. FSSPs using an LR framework should always examine the per-locus LR values generated. Such a disparity may result in an overall exclusionary LR. However, scrutiny is called for if the LR of one locus is essentially 0 and all the others are larger than 1.

A single-locus disparity needs to be further investigated to avoid a potential false exclusion. In some instances, the cause of the disparity may be determinable without looking at the reference profile (e.g., an artifact was erroneously labeled as an allele or there was an unresolved allele). In other instances, referencing the POI's genotype at the locus in question prompts the analyst to examine why that specific genotype was rejected as a possibility during PGS deconvolution. Transparency and documentation of this decision and the reasoning behind it are critical. The point at which a change in artifact determination is made should be made clear.

There are three main areas of concern relating to human factors and reinterpreting a DNA profile after the comparison to a POI's profile. The first is that the analyst will "paint the target" around the arrow,[175] leading to an association between the forensic profile and the POI when the data do not warrant such a result. The second is that if the data supports a reinterpretation but the analyst does not follow the data because of fear that changing the interpretation will appear to be biased, a false exclusion can occur. The third is that a reinterpretation will be made without transparency and documentation—whether out of hubris, fear, or a culture of institutional opacity. If reinterpretation leads to *inclusion* without documented justification, end-users and factfinders may perceive that the analyst is biased towards law enforcement, whether the change

[174] Buel E, LaFountain M, Schwartz M, Walkinshaw M. Evaluation of Capillary Electrophoresis Performance Through Resolution Measurements. *Journal of Forensic Sciences*. 2001; 46(2):341-5. doi:10.1520/jfs14968j.

[175] Thompson WC. Painting the Target around the Matching Profile: The Texas Sharpshooter Fallacy in Forensic DNA Interpretation. *Law, Probability and Risk*. 2009; 8(3):257-76. doi:10.1093/lpr/mgp013.

is scientifically defensible or not. In short, in rare instances where reinterpretation is warranted, the analyst should document the reason for the change.

Acceptable reasons for changing an initial interpretation and comparison include the following:

- The LR is essentially 0 at only one locus, and remaining single-locus profiles have LRs larger than 1.
- A biological artifact is present (e.g., tri-allele, primer binding site issue causing allelic imbalance).
- Diagnostics show that the initial NOC is too high or too low.
- Initial peak assumptions were incorrect (e.g., a previously unresolved allele, mischaracterization of a peak).
- New information changes the initial assumptions or proposition pairs (e.g., conditioning or not on a particular contributor, references submitted from relatives).
- Mixture ratios warrant accepting or rejecting possible genotype combinations (e.g., manually calculated percent contributions or IMPP).

These reasons can apply under either manual or probabilistic approaches. Considering the potential for cognitive bias, FSSP protocols should require documentation of changes and incorporate a mechanism to alert end-users when changes are made after comparison (see ***Sec. 3.3.2: Decision Justification and Recording: Transparency and Documentation***).

Recommendation 3.9: DNA analysts should not modify an original interpretation decision based on the Person of Interest's profile, except in very limited circumstances. Forensic science service providers should have clear protocols describing the circumstances under which a reevaluation is allowable, and documentation must alert the end-user that these changes occurred post-comparison.

3.7 Moving Towards PGS

Probabilistic genotyping is one of the greatest technological advancements in the interpretation of complex DNA samples. PGS uses a combination of statistical theory, biological and biochemical modeling, and computer algorithms to infer possible genotypes of a DNA profile and assign LRs.[176] PGS systems are computer applications used by analysts as tools to support the interpretation of DNA profile information and to inform opinions on the value of the findings given case-relevant propositions (see ***Sec. 3.5.3.1: Formulating Propositions in an LR***

[176] Scientific Working Group on DNA Analysis Methods (SWGDAM). *SWGDAM Guidelines for the Validation of Probabilistic Genotyping Systems*. 2015. https://www.swgdam.org/_files/ugd/4344b0_22776006b67c4a32a5ffc04fe3b56515.pdf.

This publication is available free of charge from: https://doi.org/10.6028/NIST.IR.8503

Framework). PGS has demonstrated the ability to apply biological and instrumental modeling to account for some of the complexities discussed in ***Sec. 3.4.9.2: Assessing PGS Diagnostics***. The most common PGS systems used in the United States[177] are STRmix™[178] and TrueAllele®.[179] Other systems include EuroForMix,[180] DNAStatistX,[181] LiRa,[182] MixCal6,[183] and MaSTR,[184] to name just a few.

The EWG and others[185] recommend the forensic DNA community move away from manual methods and toward probabilistic deconvolution. Although not all FSSPs have the capability or resources to implement PGS or other state-of-the-art technologies immediately and these technologies will not eliminate all human factors issues, FSSPs should work toward their implementation. While technology, such as PGS, may mitigate some human factors, it will not resolve all issues, nor will it prevent other human factors issues from arising. The choice to use a manual or probabilistic approach, or a combination of the two methods, to assist with interpreting DNA profiles can be influenced by many factors. See **Callout Box 3.7** for a discussion of the difficulties of transitioning to PGS.

[177] National Institute of Justice (NIJ). Research and Evaluation of the Implementation and Use of Continuous Probabilistic Genotyping Software to Improve the Interpretation of Forensic DNA Mixtures. Accessed March 27, 2024. https://nij.ojp.gov/funding/awards/15pnij-21-gg-02710-slfo.

[178] STRmix™. Home. Accessed March 27, 2024. https://strmix.com/.

[179] Cybergenetics. Forensics: Products and Services. Accessed March 26, 2024. https://www.cybgen.com/.

[180] EuroForMix. About. Accessed March 27, 2024. http://euroformix.com/.

[181] Benschop CCG, Hoogenboom J, Hovers P, Slagter M, Kruise D, Parag R, Steensma K, Slooten K, Nagel JHA, Dieltjes P, van Marion V, van Paassen H, de Jong J, Creeten C, Sijen T, Kneppers ALJ. DNAxs/DNAStatistX: Development and Validation of a Software Suite for the Data Management and Probabilistic Interpretation of DNA Profiles. *Forensic Science International: Genetics*. 2019; 42:81-9. doi:10.1016/j.fsigen.2019.06.015.

[182] Puch-Solis R, Clayton T. Evidential Evaluation of DNA Profiles Using a Discrete Statistical Model Implemented in the DNA LiRa Software. *Forensic Science International: Genetics*. 2014; 11:220-8. doi:10.1016/j.fsigen.2014.04.005.

[183] Slooten K. A Top-Down Approach to DNA Mixtures. *Forensic Science International: Genetics*. 2020; 46:102250. doi:10.1016/j.fsigen.2020.102250.

[184] Holland MM, Tiedge TM, Bender AJ, Gaston-Sanchez SA, McElhoe JA. MaSTR™: An Effective Probabilistic Genotyping Tool for Interpretation of STR Mixtures Associated with Differentially Degraded DNA. *International Journal of Legal Medicine*. 2022; 136(2):433-46. doi:10.1007/s00414-021-02771-0.

[185] For example, SWGDAM, ISFG, and the UK Forensic Regulator, as discussed in Coble MD, Bright JA. Probabilistic Genotyping Software: An Overview. *Forensic Science International: Genetics*. 2019; 38:219-24. doi:10.1016/j.fsigen.2018.11.009.

Callout Box 3.7: What Will it Take for All FSSPs to Use PGS?

Why don't all FSSPs use PGS to assign LRs? Roadblocks to consider when transitioning from manual to PGS methods include:

- Budgetary considerations and cycles for purchasing hardware and software and for annual maintenance contracts
- Caseload/backlogs and sample types routinely received by the FSSP
- Staffing level combined with the time and resources needed for the validation, training, and implementation of PGS
- Consideration of upgrades or disruptions to other parts of the forensic workflow that implementation of PGS may require
- An FSSP may validate PGS but use it for only a subset of cases or samples (e.g., more complex mixtures that cannot be manually interpreted)
- An FSSP may be intimidated by the challenge of interpreting mixtures that were not even attempted previously
- Decisions about whether to apply PGS retroactively to previous casework

These considerations and roadblocks are multifaceted and interconnected as summarized in **Fig. 3.2**.

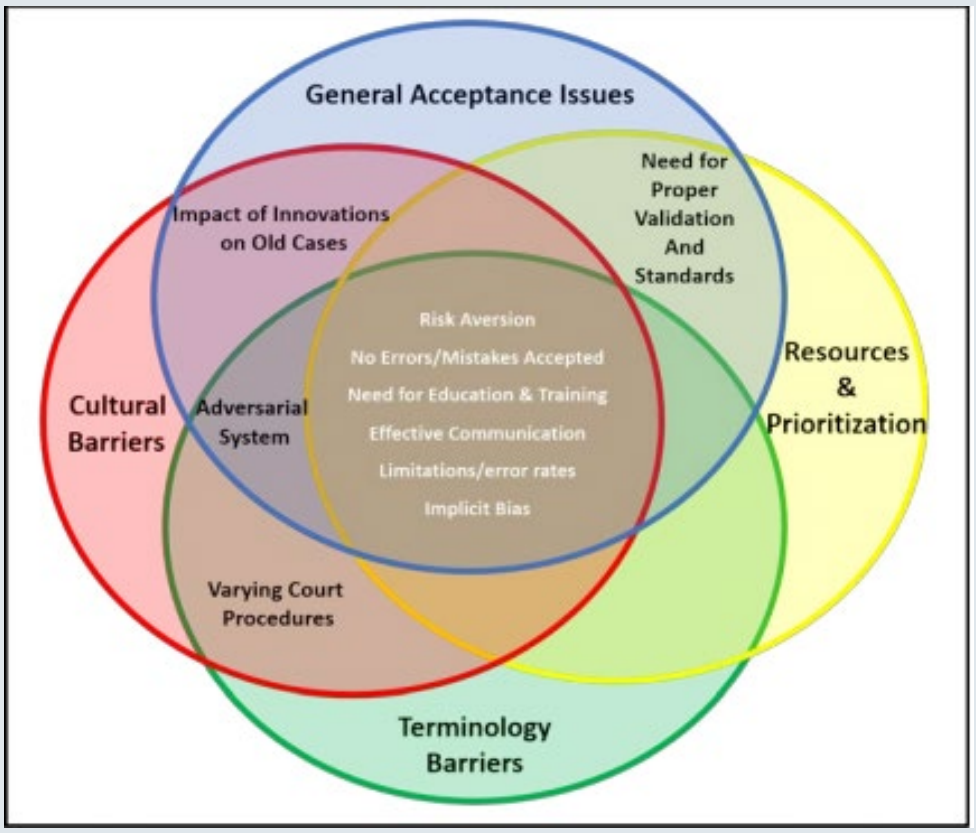

Figure 3.2: Perceived barriers in implementing new technology.

Figure from Cavanagh et al., 2019, adapted with permission.[186]

[186] Cavanagh RR, Berge A, Coute A, Fazio R, Graham T, Marshall C, Miller J, Mullen L, Sozer A, Word C. Notes from the NIST Research Innovation to Implementation in Forensic Science Symposium (RI2I). NIST Special Publication (SP) 2100-02. 2019. doi:10.6028/nist.Sp.2100-02

3.7.1 Human Factors Considerations for the PGS Developer

No matter how robust a system may be, whenever a human is involved, human factors will enter at some level (e.g., in the choice of the parameters of the model). Because there is a wide variety of PGS currently available, it would be neither possible nor desirable to discuss human factors for each individual system. Nevertheless, some guidelines for developers moving forward naturally suggest themselves. These fall into two basic categories: developer design and diagnostic outputs.

3.7.1.1 Developer Design

PGS developers should strive to eliminate unnecessary human intervention. For example, most systems today do not leave it up to an analyst to determine whether a peak is stutter, but rather rely on a statistical model that is an integral part of the system. At every step of the process, developers should ask themselves whether a potentially personal judgment by an analyst can be replaced by an automated procedure.

Where such human factors entry points exist, a developer should explain the nature and reason for these entry points. Analysts must understand when a judgment is implicitly being called for, why this is the case, how it manifests itself, and what the impact of such a judgment might be. The analyst should understand that a complex software system does not eliminate the impact of human judgment or make the entire wholly "objective."

3.7.1.2 Diagnostic Outputs

Most PGS supply diagnostic outputs that can alert the analyst to problematic situations (see **Sec. *3.4.9.2*: *Assessing PGS Diagnostics***). It is important for the developer to consider how user-friendly the presentation of the diagnostics is in the output and how clear the explanation of the diagnostics is in the user's manual. In addition, a careful explanation of the respective weight to be given to each diagnostic output should also be provided to the user. For example, how serious is the presence of an extreme mixture proportion of 99:1 versus a high value of the GR statistic?

Such input for the FSSP and analyst will likely be advisory, and the decision as to the boundaries of when to use the system will shift from the developer to the user (e.g., the minimum amount of DNA, the maximum NOC, the value of an analytic threshold if there is one) during internal validation. The developer will have an extensive base of background information and experience that is unavailable to the user, and the more that can be said and discussed in supporting materials, the better prepared the user will be to deploy the system responsibly.

Appendix 3.1: Example Decision Points in the OSAC Forensic Biology Process Map with Potential Sources of Bias and Their Impact

Decision Point in the OSAC Forensic Biology Process Map	Potential Procedural Choices	Potential Bias Sources	Example of Potential Impact
2010 – Whether there are discrepancies or issues with the evidence received **3135** – Suitability of an item submitted for analysis	Samples may not be processed due to type of case (e.g., sexual assault case with no POI)	• Severity of case • Submitting agency • Submitting individual	Analysts may evaluate discrepancies as having low or no impact on a case where there is motivation to process samples or where they know an individual or agency has (normally) good procedures.
3100 – Selection of items per evidence testing plan	Sample selection	• Severity of case • Case information • Screening methods available • Expectation for value	Items may not be considered for testing or irrelevant locations on an item are sampled. The extent to which items are tested for serology is dictated by FSSP policy and what methods they have chosen to employ compared to a **Direct-to-DNA** approach.
3370 – Screening plan	Determining what testing methods may be informative given questions in a case		
3805 – DNA batch planning	References and evidence in same extraction batch	• FSSP throughput • Case type	FSSP protocols may lend discretion to analysts about batching for liquid handling or some reference exemplars with casework. The impact could be through sensitivity of a chosen method or through increasing the risk of potential contamination.
	Liquid handling options (i.e., automation versus manual)		
4054 – DNA purification	Method of extraction	• Sample/evidence type • Validation data	Elution volume and DNA extraction method choices may lead to the need for further sample processing or manipulation. This can occur if dilution or further purification is needed. Concentration will yield a higher value at quantitation and may determine if the sample qualifies for amplification.
4072 – Concentration of sample extract	Elution volume		
4208 – Make new quant standards	Virtual standard curve (also **4234**)	• Validation data	A poor performing standard curve may misinform analysts of the true concentration of the sample. Standards that are too high will understate the quantity present in the sample, whereas
	Standard curve development (samples used)		

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Decision Point in the OSAC Forensic Biology Process Map	Potential Procedural Choices	Potential Bias Sources	Example of Potential Impact
			standards that are too low will overstate the quantity.
4270 – Quant results consistent with expectation	Observation of internal PCR control shift (inhibition) Observation of degradation Male: Autosomal ratio present	• Validation data	Quantitative results should be consistent with expectations set during validation. The characteristics of degradation, inhibition, and a mixture of male and autosomal DNA should be well categorized and understood.
4400 – Kit selection (STR typing)	Volume or concentration of DNA input Number of cycles Reaction volume	• Validation data	The amount of DNA and concentration targeted as well as the cycle numbers for STR typing should primarily be based on validation data to target the amount of DNA and PCR cycle number to reliably produce enough allelic information for interpretation.
4624 – Setup of CE instrument for separation and detection	Injection voltage and time	• Case type • Sample type • Validation data	Validation data should support the decisions analysts may make in selecting different injection voltages or times. FSSP procedures should be in place and well defined to prevent procedural drift. A higher voltage injection, or one over a long time, may increase the intensity of the peaks identified, possibly resulting in more analyzable data or higher baseline noise.
6000 – NOC	Manual assessment versus assistance of software	• Case type • Case information • Other analyst's decisions • Presence of expected contributors • FSSP's SOPs	NOC assessment may have a direct impact on suitability assessment. If the FSSP's SOPs do not allow the processing of five-person mixtures, an analyst may be more inclined to determine four contributors are present. This impact can be exacerbated if it is a serious case.

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Decision Point in the OSAC Forensic Biology Process Map	Potential Procedural Choices	Potential Bias Sources	Example of Potential Impact
6014 – Setting the number of assumed contributors	Conditioning	• Case type • Case information	If an analyst is told that the complaint had intercourse with a boyfriend 48 hours prior to an alleged sexual assault, they may be more inclined to attribute low-level alleles to the boyfriend than to drop-in or a different unknown individual.
6118 – Is the unresolved mixture profile suitable for comparison? (manual)	Analyst NOC consideration	• Case type • Case information • Other analyst's decisions • Presence of assumed contributors • FSSP's SOPs • Other items in the same case	Analysts may be unsure if a mixture is from two contributors or more than two contributors and may be more inclined to call two contributors (if this is the suitability limit) when considering the perceived importance of evidence or severity of the crime.
	Determining which loci to use for comparison or statistics		
6258 – Is observed discordance explainable? (manual)	Post-comparison artifact versus allele designation	• Case type • Case information • Other analyst's decisions • Presence of assumed contributors • FSSP's SOPs	Analysts may be more inclined to designate an allele as an artifact to better align with their assumed NOC.
6524/6556 – Proceeding with LR deconvolution based on quality metrics	Reevaluate NOC, allele designations, or input data	• Case type • Case information • Other analyst's decisions	In the presence of highly biasing case information (e.g., violent homicide/rape details), an analyst may decide to re-genotype a profile to remove a peak at a particular locus if an exculpatory LR is provided, deciding a posteriori that the peak is artifactual.
	Re-amplification		
	Re-run with increased iterations		
	Adjust software mixture proportions		
	Change degradation thresholds, burn-in iterations, assumptions, propositions, or NOC		

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Decision Point in the OSAC Forensic Biology Process Map	Potential Procedural Choices	Potential Bias Sources	Example of Potential Impact
7108 – Are all technical review evaluation criteria acceptable?	Technical review and conflict resolution	• Primary examiner identity • Result • FSSP's SOPs	Analysts may be more likely to agree with the opinions of individuals who are more senior or experienced than they are (i.e., halo effect[187]) or more likely to disagree with the opinions of individuals whom they have a personal dislike for.

[187] Nisbett RE, Wilson TD. The Halo Effect: Evidence for Unconscious Alteration of Judgments. *Journal of Personality and Social Psychology*. 1977; 35:250-6. doi:10.1037/0022-3514.35.4.250.

4. Quantitative and Qualitative Ways to Express DNA Results

4.1 Introduction and Scope

This chapter describes the different ways that DNA analysts can express DNA comparison and serological screening results. At times, the most scientifically robust way to express DNA results can be at odds with comprehensibility. The currently available empirical literature on laypersons' comprehension of forensic results presents an ambiguous, and at times contradictory, picture on how results should be presented.[188] Studies vary significantly in how evidence is presented to mock jurors, how comprehension is measured, which disciplines are used for testing, and which verbal statements or numerical expressions are tested and compared. Overall, the literature appears to demonstrate that jurors are inconsistent in their interpretation of evidence presented in equivalent ways,[189] that jurors may not assign the same *value*[190] to the evidence as the examiner intends[191] and that different types of statements can be misunderstood.[192] The Expert Working Group (EWG) has considered the current literature and its collective experience to inform the practices suggested in this chapter.

Implementation of recommendations in this chapter will require a DNA community–wide effort. Forensic science service providers (FSSPs) need to provide analysts with the appropriate resources and training opportunities, and criminal justice partners need to receive training to understand and use forensic DNA results.

The topics discussed in this chapter are closely related to those in ***Chapter 3: Interpretation***, ***Chapter 5: Reporting***, and ***Chapter 6: Pre-Trial Preparation and Testimony*****.** Recommendations related to how DNA analysts should express DNA results also apply to how they should report DNA results.

[188] Eldridge H. Juror Comprehension of Forensic Expert Testimony: A Literature Review and Gap Analysis. *Forensic Science International: Synergy*. 2019; 1:24-34. doi:10.1016/j.fsisyn.2019.03.001; Martire KA. Clear Communication through Clear Purpose: Understanding Statistical Statements Made by Forensic Scientists. *Australian Journal of Forensic Sciences*. 2018; 50(6):619-27. doi:10.1080/00450618.2018.1439101.

[189] Thompson WC, Grady RH, Lai E, Stern HS. Perceived Strength of Forensic Scientists' Reporting Statements About Source Conclusions. *Law Probability & Risk*. 2018; 17(2):133-55. doi:10.1093/lpr/mgy012.

[190] The EWG engaged in many conversations as to the appropriate word to use when describing DNA results: *weight, value, or strength*. In essence, these can be applied interchangeably; however, for the purposes of this chapter, we chose *value*.

[191] Busey T, Klutzke M. Calibrating the Perceived Strength of Evidence of Forensic Testimony Statements. *Science & Justice*. 2023; 63(1):38-53. doi:10.1016/j.scijus.2022.10.003; Martire KA, Kemp RI, Watkins I, Sayle MA, Newell BR. The Expression and Interpretation of Uncertain Forensic Science Evidence: Verbal Equivalence, Evidence Strength, and the Weak Evidence Effect. *Law and Human Behavior*. 2013; 37(3):197-207. doi:10.1037/lhb0000027.

[192] Thompson WC, Newman EJ. Lay Understanding of Forensic Statistics: Evaluation of Random Match Probabilities, Likelihood Ratios, and Verbal Equivalents. *Law and Human Behavior*. 2015; 39(4):332-49. doi:10.1037/lhb0000134.

4.2 Why DNA Analysts Should Not Make Source Attributions

Source attribution consists of identifying the Person of Interest (POI)[193] as the source of (or as a contributor to) a questioned sample. For example, an opinion that "the POI is the source of the crime-scene sample" is a source attribution. So is a statement that "it is highly probable (but not certain) that the POI is the source of the crime-scene sample." And so is a statement that "the probability that the POI is the source of the crime scene sample is 99.1%" (or any other probability value). In the legal context, an opinion on source should be made by considering all the evidence in the case as well as the consequences of the decision. This task is the responsibility of the factfinder, not the DNA analyst.[194] However, the DNA analyst must describe the value that the DNA data have in reaching a source conclusion.

The value of the DNA comparisons should be expressed using probabilities rather than categorical terms.[195] The factfinder can then, theoretically, incorporate the value of the results (e.g., likelihood ratio) as part of their decision-making.[196] The next subsection explains how this evaluation of the evidence can be done by describing how much more (or less) strongly the data point to the POI as the source than to some other individual.

4.3 The Likelihood Ratio

The likelihood ratio (LR) allows analysts to quantify the value of scientific results (E) given two mutually exclusive propositions (H_1, H_2) formed using conditioning information (I) derived from case information, known or assumed.[197] As presented in **Equation 4.1**, the LR can be defined as a ratio of two conditional probabilities.

[193] POI is not synonymous with suspect. A POI can extend to any individual needing to be compared to a DNA profile, including those compared for elimination purposes.

[194] Biedermann A. The Strange Persistence of (Source) "Identification" Claims in Forensic Literature through Descriptivism, Diagnosticism and Machinism. *Forensic Science International: Synergy*. 2022; 4:100222. doi:doi:10.1016/j.fsisyn.2022.100222; Biedermann A, Bozza S, Taroni F. Decision Theoretic Properties of Forensic Identification: Underlying Logic and Argumentative Implications. *Forensic Science International*. 2008; 177(2-3):120-32. doi:10.1016/j.forsciint.2007.11.008; Biedermann A, Bozza S, Taroni F. The Decisionalization of Individualization. *Forensic Science International*. 2016; 266:29-38. doi:10.1016/j.forsciint.2016.04.029; Cole SA. Forensics without Uniqueness, Conclusions without Individualization: The New Epistemology of Forensic Identification. *Law, Probability and Risk*. 2009; 8(3):233-55. doi:10.1093/lpr/mgp016; Kaye DH. Probability, Individualization, and Uniqueness in Forensic Science Evidence: Listening to the Academics. *Brooklyn Law Review*. 2010; 75(4):1163-85. ; Lindley DV. A Problem in Forensic Science. *Biometrika*. 1977; 64(2):207-13. doi:10.1093/biomet/64.2.207; Saks MJ, Koehler JJ. The Individualization Fallacy in Forensic Science Evidence. *Vanderbilt Law Review*. 2008;61:199-219. Accessed March 27, 2024. https://scholarship.law.vanderbilt.edu/vlr/vol61/iss1/4; Stoney DA. What Made Us Ever Think We Could Individualize Using Statistics? *Journal of the Forensic Science Society*. 1991; 31(2):197-9. doi:10.1016/s0015-7368(91)73138-1.

[195] Stoney DA. What Made Us Ever Think We Could Individualize Using Statistics? *Journal of the Forensic Science Society*. 1991; 31(2):197-9. doi:10.1016/s0015-7368(91)73138-1.

[196] Finkelstein MO, Fairley WB. A Bayesian Approach to Identification Evidence. *Harvard Law Review*. 1970; 83(3):489-517. doi:10.2307/1339656.

[197] Evett IW. Towards a Uniform Framework for Reporting Opinions in Forensic Science Casework. *Science & Justice*. 1998; 38(3):198-202. doi:10.1016/S1355-0306(98)72105-7; Finkelstein MO, Fairley WB. A Bayesian Approach to Identification Evidence. *Harvard Law Review*. 1970; 83(3):489-517. doi:10.2307/1339656; Hicks T, Buckleton J, Castella V, Evett IW, Jackson G. A Logical Framework for Forensic DNA Interpretation. *Genes (Basel)*. 2022; 13(6):957. doi:10.3390/genes13060957.

$$LR = \frac{Pr(E|H1, I)}{Pr(E|H2, I)}$$

Equation 4.1: The LR General Formula.

The numerator is the probability of the results given the first proposition and the case information, and the denominator is the probability of the results given the second proposition and the case information. An LR greater than 1 indicates that the results support the first proposition compared to the second proposition. An LR less than 1 indicates that the results support the second proposition compared to the first. An LR of 1 is obtained when the results provide equal support for both propositions. In that case, the observations provide no assistance to the factfinder for choosing between the stated propositions – the results are uninformative.[198] Numerous books and standards[199] have recommended the use of the LR in forensic science as it allows the analyst to quantify the value of the forensic results in a balanced, logical, robust, and transparent manner.[200]

The EWG believes that LRs are the most effective and efficient way for analysts to assess and communicate the value of the findings because:

- LRs enable the end-user to consider the value of the results given two views, satisfying the criteria of balance (see **Sec. *3.5.3*: *Comparison to a POI***).
- LRs are a ratio of two conditional probabilities, which allows the analyst or end-user to reason in the face of uncertainty.
- LRs are assigned based on case-relevant information.

[198] Lindley DV. *Understanding Uncertainty*. John Wiley & Sons, Ltd.: Hoboken, NJ, 2006.

[199] Aitken C, Stoney DA. *The Use of Statistics in Forensic Science*. Taylor & Francis: London, UK, 1991. doi:10.1201/b12618; Aitken C, Taroni F. *Statistics and the Evaluation of Evidence for Forensic Scientists*. 2nd ed. John Wiley & Sons, Ltd: West Sussex, UK, 2004. doi:10.2307/1268932; Aitken C, Taroni F, Bozza S. *Statistics and the Evaluation of Evidence for Forensic Scientists*. 3rd ed. John Wiley & Sons, Ltd: Hoboken, NJ, 2021. ; Buckleton J, Bright JA, Taylor D. *Forensic DNA Evidence Interpretation*. 2nd ed. CRC Press: Boca Raton, 2016. doi:10.4324/9781315371115; European Network of Forensic Science Institutes (ENFSI). *ENFSI Guideline for Evaluative Reporting in Forensic Science: Strengthening the Evaluation of Forensic Results across Europe (STEOFRAE), Version 3.0*. 2015. https://enfsi.eu/wp-content/uploads/2016/09/m1_guideline.pdf; Evett IW, Weir BS. *Interpreting DNA Evidence: Statistical Genetics for Forensic Scientists*. Sinauer Associates Inc,: Sunderland, MA, 1998. ; Finkelstein MO, Fairley WB. A Bayesian Approach to Identification Evidence. *Harvard Law Review*. 1970; 83(3):489-517. doi:10.2307/1339656; Gill P, Hicks T, Butler JM, Connolly E, Gusmao L, Kokshoorn B, Morling N, van Oorschot RAH, Parson W, Prinz M, Schneider PM, Sijen T, Taylor D. DNA Commission of the International Society for Forensic Genetics: Assessing the Value of Forensic Biological Evidence - Guidelines Highlighting the Importance of Propositions. Part II: Evaluation of Biological Traces Considering Activity Level Propositions. *Forensic Science International: Genetics*. 2020; 44:102186. doi:10.1016/j.fsigen.2019.102186; Gill P, Hicks T, Butler JM, Connolly E, Gusmao L, Kokshoorn B, Morling N, van Oorschot RAH, Parson W, Prinz M, Schneider PM, Sijen T, Taylor D. DNA Commission of the International Society for Forensic Genetics: Assessing the Value of Forensic Biological Evidence - Guidelines Highlighting the Importance of Propositions: Part I: Evaluation of DNA Profiling Comparisons Given (Sub-) Source Propositions. *Forensic Science International: Genetics*. 2018; 36:189-202. doi:10.1016/j.fsigen.2018.07.003; Kaye DH. *The Double Helix and the Law of Evidence*. Harvard University Press: Cambridge, MA, 2010. ; Robertson B, Vignaux GA, Berger CEH. *Interpreting Evidence*. 2nd ed. Wiley & Sons: Chichester, UK, 2016.

[200] Evett IW, Jackson G, Lambert JA, McCrossan S. The Impact of the Principles of Evidence Interpretation on the Structure and Content of Statements. *Science & Justice*. 2000; 40(4):233-9. doi:10.1016/S1355-0306(00)71993-9; Hicks T, Buckleton J, Castella V, Evett IW, Jackson G. A Logical Framework for Forensic DNA Interpretation. *Genes (Basel)*. 2022; 13(6):957. doi:10.3390/genes13060957; Jackson G. The Scientist and the Scales of Justice. *Science & Justice*. 2000; 40(2):81-5. doi:10.1016/S1355-0306(00)71947-2; Jackson G, Jones S, Booth G, Champod C, Evett IW. The Nature of Forensic Science Opinion - a Possible Framework to Guide Thinking and Practice in Investigations and in Court Proceedings. *Science & Justice*. 2006; 46(1):33-44. doi:10.1016/s1355-0306(06)71565-9.

- In ground-truth experiments, LRs have been shown to be an efficient metric that helps discriminate propositions, provided the propositions adhere to case information.
- LRs have been used in paternity and missing persons cases for many decades, as well as in other forensic disciplines.

4.3.1 Conditioning Information and Formulating Propositions

The LR depends not only on the two competing propositions but also on case information that the analyst knows or assumes to be true. This conditioning information, sometimes referred to as the framework of circumstances, helps the analyst formulate propositions to be considered (see ***Sec. 3.5.3.1: Formulating Propositions in an LR Framework***).[201] If the questions revolve around whose DNA may be present, then the propositions might be:

- A POI and one unknown individual are the source of the DNA mixture.
- Two unknown individuals are the source of the DNA mixture.

Typically, the unknown individuals are assumed to be unrelated; however, propositions can incorporate related individuals as well (see ***Sec. 3.5.4: Considering Relatives***).

An LR does not provide information about any propositions other than the two that are considered and expresses only the value of the results considering this pair of propositions. Thus, an LR tells us how many times more probable the DNA findings are given one proposition and the case information as opposed to the same information but a different proposition. This relative probability is sometimes described as the degree or amount of support. Care must be taken not to confuse this with a statement about which proposition is the most probable.

The most supported proposition is not necessarily the most probable, as the probability of the proposition depends on all the elements in the case and therefore only partly on the DNA results. This is why the so-called posterior probability is not in the domain of the DNA analyst (see ***Sec. 6.12.1: Properly Explaining the Quantitative Value of the Results***).

The two probabilities that make up the LR cannot be inferred from each other, as they consider the probability of the same observations given different propositions. Therefore, the fact that the denominator is small does not imply that the numerator is large.

[201] Cook R, Evett IW, Jackson G, Jones PJ, Lambert JA. A Hierarchy of Propositions: Deciding Which Level to Address in Casework. *Science & Justice*. 1998; 38(4):231-9. doi:10.1016/S1355-0306(98)72117-3.

4.3.2 Bayes' Theorem and Prior Odds

Bayes' theorem is a mathematical formula that can be used to update one's belief about a set of propositions in light of new evidence.[202] Bayes' theorem is seldom *explicitly* used in courts.[203] Generally, the factfinder will combine the different pieces of evidence intuitively. This does not, of course, preclude the use of an LR to express the value of the results.

Bayes' theorem may be depicted in an *odds form*. *Odds* are the ratio of the probability of the proposition being true divided by the probability of it being false. The formula presented in **Equation 4.2** shows that **prior odds**, multiplied by an LR, equal **posterior odds**. Where odds relate to the probability of the propositions (i.e., alleged facts), prior odds are the odds in favor of a proposition *without* considering the evidence, and posterior odds are the odds in favor of a proposition considering new evidence.

Prior odds depend on the other information (e.g., case information) and non-DNA evidence presented in a case; as such, they are the province of the factfinder. Bayes' theorem allows for separation of the roles of the factfinder (probability of propositions) and the analyst (probability of the results).

$$\underbrace{\frac{Pr(H_1 \mid I)}{Pr(H_2 \mid I)}}_{\text{Prior Odds}} \; x \; \underbrace{\frac{Pr(E \mid H_1, I)}{Pr(E \mid H_2, I)}}_{\text{Likelihood Ratio}} = \underbrace{\frac{Pr(H_1 \mid E, I)}{Pr(H_2 \mid E, I)}}_{\text{Posterior Odds}}$$

Equation 4.2: Odds form of Bayes' theorem. The LR is the role of the DNA analyst while the prior and posterior odds are the province of the factfinder.

To illustrate that the probability of the propositions depends not only on the results but also on the other information, **Table 4.1** demonstrates the change in posterior odds and posterior probabilities using the same LR but different prior odds. In this example, the LR remains the same (1 million), but prior odds are varied.

When the prior odds are 1 to 10 million, the most favored proposition is the second with a probability of 91%. When the prior odds are equal to 1/LR, the posterior probability of the proposition is 50%. Here we see that prior odds are crucial to assign posterior odds and that the probability of the propositions depends both on the value of the results and the other elements.

[202] Blair JP, Rossmo DK. Evidence in Context: Bayes' Theorem and Investigations. *Police Quarterly*. 2010; 13(2):123-35. doi:10.1177/1098611110365686; Evett IW. Bayesian Inference and Forensic Science: Problems and Perspectives. *Journal of the Royal Statistical Society: Series D (The Statistician)*. 1987; 36(2-3):99-105. doi:10.2307/2348502; Taroni F, Biedermann A. Uncertainty in Forensic Science: Experts, Probabilities and Bayes' Theorem. *Italian Journal of Applied Statistics*. 2015; 27(2):129-144. ; Taroni F, Bozza S, Biedermann A, Garbolino P, Aitken C. *Data Analysis in Forensic Science: A Bayesian Decision Perspective*. John Wiley & Sons: West Sussex, UK, 2010. doi:10.1002/9780470665084.

[203] Except perhaps in paternity cases; Kaye DH. Plemel as a Primer on Proving Paternity. *Willamette Law Review*. 1988; 24(4):867-83.

This also shows why categorical statements (see ***Sec. 4.5*: *Qualitative Expressions of DNA Comparison Results***) that quash uncertainty are inappropriate.

Table 4.1: The effect of prior odds on posterior odds and probabilities.

Prior Odds	LR	Posterior Odds	Posterior Probability of H_1	Posterior Probability of H_2
1 to 10 million	1,000,000	1 to 10	9%	91%
1 to 1,000,000	1,000,000	1 to 1	50%	50%
1 to 10,000	1,000,000	100 to 1	99%	1%
1 to 1	1,000,000	1,000,000 to 1	99.9999%	0.0001%

Figure from Hicks et al., 2022, adapted with permission.[204]

To compute posterior odds, one multiplies prior odds with the LR. Posterior probabilities can then be calculated using the formula: when odds are a:b, then the probability of the first proposition is equal to a/(a+b).

Recommendation 4.1: Forensic science service providers should use likelihood ratios to evaluate DNA results.

4.3.3 Precision and Accuracy in LRs

Concepts like "precision" and "accuracy" are not appropriate in the LR framework. The LR is not a measurement in the sense of a quantity of, for example, purported drugs, but rather an expression used to describe if and how much the DNA results provide support for one proposition versus another.[205] There is not one true LR, as the LR will depend on the analyst's and the model's assumptions (e.g., **allele frequency** data, sampling uncertainty, co-ancestry coefficient, population substructure) and propositions.

Because probabilities (and LRs) depend on knowledge, data, and modeling assumptions, sensitivity analyses can be used to evaluate the impact that changes to these dependencies will have on the LR value.[206] Some argue that the impact of these modeling imperfections pales in comparison to other variabilities (e.g., pipetting, injection to injection variation)[207] and the formulation of pertinent propositions. Therefore, from a human factors perspective, it is useful

[204] Hicks T, Buckleton J, Castella V, Evett IW, Jackson G. A Logical Framework for Forensic DNA Interpretation. *Genes (Basel)*. 2022; 13(6):957. doi:10.3390/genes13060957.

[205] European Network of Forensic Science Institutes (ENFSI). *Best Practice Manual for Human Forensic Biology and DNA Profiling ENFSI-DNA-Bpm-03, Version 01*. 2022. https://enfsi.eu/wp-content/uploads/2022/12/ENFSI-DNA-BPM-03.pdf.

[206] Riman S, Iyer H, Vallone PM. Examining Performance and Likelihood Ratios for Two Likelihood Ratio Systems Using the PROVEDIt Dataset. *PloS One*. 2021; 16(9):e0256714. doi:10.1371/journal.pone.0256714.

[207] Bright JA, Stevenson KE, Curran JM, Buckleton J. The Variability in Likelihood Ratios Due to Different Mechanisms. *Forensic Science International: Genetics*. 2015; 14:187-90. doi:10.1016/j.fsigen.2014.10.013.

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to consider what factors may cause variation between the LRs produced on the same DNA profile and how that variation is expressed to end-users.

Another useful concept when comparing different models, or when developers put their model to the test, is known as calibration. A well-calibrated system produces large values for LRs when the POI is a true contributor and small LR values when the POI is a true non-contributor. Publications supporting probabilistic genotyping calculations include extensive studies of ground-truth cases to demonstrate that the system is well calibrated.[208]

A mathematical relationship known as "Turing's rule" can help with understanding if an LR model is well-calibrated. Turing's Rule states that the expected LR for a false proposition is 1 if the model is performing well.[209] In ground-truth experiments, if the model is well calibrated, when an LR of 1 million is computed given sub-source propositions, we would expect roughly 1 in every million non-donor DNA profiles to yield a LR of 1 million when compared to the DNA evidence profile.

We would also expect 999,999 out of every million non-donor profiles to yield an LR of 0 when compared to the DNA evidence profile. The average LR of these ground-truth comparisons is then 1. This type of calibration assessment tool is not meant to be a substitute for expressing the value of the DNA comparison in any given case because it may lead to misunderstanding, such as the expected value or defense attorney fallacies.[210]

Even if the LR is well calibrated and sensitivity analyses have been performed, the LR should not be expressed to a single point of implied "precision." Because of uncertainties in the modeling assumptions, the sampling of alleles, and the effects of population substructure, DNA analysts should report LRs to only one significant figure. For example, if an LR of 10,256.32 was computed, the analyst could report that the results are of the order of 10,000 times more probable under H_1 than under H_2. This allows the analyst to convey that it is the order of magnitude—not the pinpoint value—that is important. Alternatively, DNA analysts could use log(LR)s[211] along with

[208] Bright JA, Cheng K, Kerr Z, McGovern C, Kelly H, Moretti TR, Smith MA, Bieber FR, Budowle B, Coble MD, Alghafri R, Allen PS, Barber A, Beamer V, Buettner C, Russell M, Gehrig C, Hicks T, Charak J, Cheong-Wing K, Ciecko A, Davis CT, Donley M, Pedersen N, Gartside B, Granger D, Greer-Ritzheimer M, Reisinger E, Kennedy J, Grammer E, Kaplan M, Hansen D, Larsen HJ, Laureano A, Li C, Lien E, Lindberg E, Kelly C, Mallinder B, Malsom S, Yacovone-Margetts A, McWhorter A, Prajapati SM, Powell T, Shutler G, Stevenson K, Stonehouse AR, Smith L, Murakami J, Halsing E, Wright D, Clark L, Taylor DA, Buckleton J. STRmix™ Collaborative Exercise on DNA Mixture Interpretation. *Forensic Science International: Genetics*. 2019; 40:1-8. doi:10.1016/j.fsigen.2019.01.006; Bright JA, Jones Dukes M, Pugh S, Evett I, Buckleton J. Applying Calibration to LRs Produced by a DNA Interpretation Software. *Australian Journal of Forensic Sciences*. 2021; 53(2):147-53. doi:doi: 10.1080/00450618.2019.1682668.

[209] Good IJ. *Probability and the Weighing of Evidence*. Charles Griffin & Company Limited: London, UK, 1950.

[210] Evett IW, Weir BS. *Interpreting DNA Evidence: Statistical Genetics for Forensic Scientists*. Sinauer Associates Inc,: Sunderland, MA, 1998. ; Thompson WC, Schumann EL. Interpretation of Statistical Evidence in Criminal Trials: The Prosecutor's Fallacy and the Defense Attorney's Fallacy. *Law and Human Behavior*. 1987; 11(3):167-87. doi:10.1007/bf01044641.

[211] Good IJ. *Probability and the Weighing of Evidence*. Charles Griffin & Company Limited: London, UK, 1950.

supplemental verbal qualifiers[212] that are in rough correspondence to orders of magnitude of the LR to express the weight of the evidence.

Recommendation 4.2: To avoid conveying an unsupported level of precision, forensic science service providers should express likelihood ratios as an order of magnitude or to one significant figure.

4.3.4 Uncertainty and Error in LRs

In general, there seems to be a consensus that the concept of uncertainty does not apply to LRs and that they encapsulate some kind of error uncertainty.[213] Taylor and Balding state there is "little or no benefit, and possibly some confusion, from reporting alongside the LR an error rate resulting from measurement or analytical error that is already accounted for in the LR calculation."[214]

End-users should not dismiss errors that are independent of modeling or computational effects of PGS and LRs. For example, the rate of contamination may be higher than many reported statistical values and, in some cases, will have a significant impact on the evaluation of the findings.[215]

Research by Koehler et al. indicates that end-users may find it challenging to combine probabilities appropriately,[216] which could lend support for an aggregation of multiple error sources within an LR. However, although the potential for gross error (e.g., human errors such as contamination, sample switching, mistakes in reading or recording data) could be incorporated

[212] Aitken C, Taroni F. A Verbal Scale for the Interpretation of Evidence. *Science & Justice*. 1998; 38(4):279-281. doi:10.1016/S1355-0306(98)72128-8.

[213] Balding DJ, Steele CD. *Weight-of-Evidence for Forensic DNA Profiles*. 2nd ed. John Wiley & Sons, Ltd: West Sussex, UK, 2015. doi:10.1002/9781118814512; Kloosterman A, Sjerps M, Quak A. Error Rates in Forensic DNA Analysis: Definition, Numbers, Impact and Communication. *Forensic Science International: Genetics*. 2014; 12:77-85. doi:10.1016/j.fsigen.2014.04.014; Ommen DM, Saunders CP, Neumann C. An Argument against Presenting Interval Quantifications as a Surrogate for the Value of Evidence. *Science & Justice*. 2016; 56(5):383-7. doi:10.1016/j.scijus.2016.07.001; Slooten K. Likelihood Ratio Distributions and the (Ir)Relevance of Error Rates. *Forensic Science International: Genetics*. 2020; 44:102173. doi:10.1016/j.fsigen.2019.102173; Taylor D, Balding D. How Can Courts Take into Account the Uncertainty in a Likelihood Ratio? *Forensic Science International: Genetics*. 2020; 48:102361. doi:10.1016/j.fsigen.2020.102361.

[214] Taylor D, Balding D. How Can Courts Take into Account the Uncertainty in a Likelihood Ratio? *Forensic Science International: Genetics*. 2020; 48:102361. doi:10.1016/j.fsigen.2020.102361. p. 2.

[215] Kloosterman A, Sjerps M, Quak A. Error Rates in Forensic DNA Analysis: Definition, Numbers, Impact and Communication. *Forensic Science International: Genetics*. 2014; 12:77-85. doi:10.1016/j.fsigen.2014.04.014.

[216] Koehler JJ, Chia A, Lindsey S. The Random Match Probability in DNA Evidence: Irrelevant and Prejudicial? *Jurimetrics: The Journal of Law, Science, and Technology*. 2009; 35(2):201-19.

into an LR[217] or Bayesian network,[218] the consideration of such errors may not be relevant to all cases or all profiles within a case. Taylor and Balding, therefore, recommend reporting an LR separate to these types of errors.[219] Kloosterman et al. agree that gross error should be reported separately, while also conveying to the factfinder the circumstances, such as contamination or planted evidence, under which the statistical value would be irrelevant.[220]

4.3.5 Applying a Reporting Cap

LRs can often be very large (or Random Match Probabilities [RMPs] very small), reaching numbers that laypersons may never have heard (e.g., quintillions). Although some FSSPs routinely report these numbers, others have implemented a reporting cap. A reporting cap sets an upper bound whereby any number above that threshold is reported at that threshold. The United Kingdom,[221] Ireland, and Switzerland use an upper bound of 1 billion (corresponding to an RMP of 1 in 1 billion), while Australia uses 100 billion,[222] and Denmark uses 1 million.[223]

Population genetics models are used to assign the probability of a profile in a population assuming complete linkage disequilibrium. However, this assumption is not strictly true, and the accuracy and robustness of very small probabilities are all but impossible to verify empirically. Therefore, these models could lead to an overstatement of the strength of the DNA comparison.[224] For the use of one 15-locus kit, Hopwood et al.[225] recommend an upper bound of

[217] Balding DJ, Steele CD. *Weight-of-Evidence for Forensic DNA Profiles*. 2nd ed. John Wiley & Sons, Ltd: West Sussex, UK, 2015. doi:10.1002/9781118814512; Fenton N, Neil M, Hsu A. Calculating and Understanding the Value of Any Type of Match Evidence When There Are Potential Testing Errors. *Artificial Intelligence and Law*. 2013; 22(1):1-28. doi:10.1007/s10506-013-9147-x; Taroni F, Aitken C, Garbolino P, Biedermann A. *Bayesian Networks and Probabilistic Inference in Forensic Science*. John Wiley & Sons, Ltd: West Sussex, England, 2006. doi:10.1002/0470091754; Thompson WC. Subjective Interpretation, Laboratory Error and the Value of Forensic DNA Evidence: Three Case Studies. *Genetica*. 1995; 96(1-2):153-68. doi:10.1007/BF01441161; Thompson WC, Taroni F, Aitken CG. How the Probability of a False Positive Affects the Value of DNA Evidence. *Journal of Forensic Sciences*. 2003; 48(1):47-54. doi:10.1520/JFS2001171.

[218] Taroni F, Aitken C, Garbolino P, Biedermann A. *Bayesian Networks and Probabilistic Inference in Forensic Science*. John Wiley & Sons, Ltd: West Sussex, England, 2006. doi:10.1002/0470091754.

[219] Taylor D, Balding D. How Can Courts Take into Account the Uncertainty in a Likelihood Ratio? *Forensic Science International: Genetics*. 2020; 48:102361. doi:10.1016/j.fsigen.2020.102361.

[220] Balding DJ, Steele CD. *Weight-of-Evidence for Forensic DNA Profiles*. 2nd ed. John Wiley & Sons, Ltd: West Sussex, UK, 2015. doi:10.1002/9781118814512; Kloosterman A, Sjerps M, Quak A. Error Rates in Forensic DNA Analysis: Definition, Numbers, Impact and Communication. *Forensic Science International: Genetics*. 2014; 12:77-85. doi:10.1016/j.fsigen.2014.04.014.

[221] Forensic Science Regulator. *Codes of Practice and Conduct: Development of Evaluative Opinions. FSR-C-118, Issue 1*. 2021. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/960051/FSR-C-118_Interpretation_Appendix_Issue_1__002_.pdf.

[222] Reporting cap of 100 billion is in line with advice from the Biology Special Advisory Group in Australia.

[223] Personal communication with Bo Thisted Simonsen, PhD, Director of Section of Forensic Genetics, Institute of Forensic Medicine at University of Copenhagen.

[224] Foreman LA, Evett IW. Statistical Analyses to Support Forensic Interpretation for a New Ten-Locus STR Profiling System. *International Journal of Legal Medicine*. 2001; 114(3):147-55. doi:10.1007/s004140000138; Hopwood AJ, Puch-Solis R, Tucker VC, Curran JM, Skerrett J, Pope S, Tully G. Consideration of the Probative Value of Single Donor 15-Plex STR Profiles in UK Populations and Its Presentation in UK Courts. *Science & Justice*. 2012; 52(3):185-90. doi:10.1016/j.scijus.2012.05.005; Vergeer P, van Es A, de Jongh A, Alberink I, Stoel R. Numerical Likelihood Ratios Outputted by LR Systems Are Often Based on Extrapolation: When to Stop Extrapolating? *Science & Justice*. 2016; 56(6):482-91. doi:10.1016/j.scijus.2016.06.003.

[225] Hopwood AJ, Puch-Solis R, Tucker VC, Curran JM, Skerrett J, Pope S, Tully G. Consideration of the Probative Value of Single Donor 15-Plex STR Profiles in UK Populations and Its Presentation in UK Courts. *Science & Justice*. 2012; 52(3):185-90. doi:10.1016/j.scijus.2012.05.005.

1 billion if the alternative source of the DNA is an unknown, unrelated individual; a half sibling; an uncle/aunt; a nephew/niece; or a first cousin. If, however, the alternative source is a parent or child (whose DNA is not available), then the bound should drop to an LR of 10 million. When the source is an unavailable sibling, they recommend lowering the cap to 100,000 (see **Table 4.2**).

Table 4.2: Proposed caps for reporting the value of DNA profile comparisons adapted from Hopwood et al[226]

Relationship With POI	Upper Bound LR
Sibling	1×10^5 (100,000)
Parent/child	1×10^7 (10 million)
Half sibling or uncle/nephew	1×10^9 (1 billion)
First cousin	1×10^9 (1 billion)
Unrelated (same subpopulation)	1×10^9 (1 billion)
Unrelated (different subpopulations)	1×10^9 (1 billion)

Table adapted from Hopwood, et al., (2012)[227]

Factfinders could misinterpret extreme numbers (in particular, those above the world population) to mean that no one else in the world could have that DNA profile. For example, a cognitive fallacy—the *expected value fallacy*[228]—is to believe that if the probability of a DNA profile is one in one million, then only one individual in a population of one million could have that profile. A reporting cap set below the world's population would preclude the misinterpretation of an expected value of no more than one unrelated, matching individual in the world's population as definitive proof of uniqueness in that population.[229]

Choosing the value for a cap depends first on the belief one has in the model used to compute the probabilities and secondly on how the number will be understood. For communication

[226] Ibid.

[227] Ibid.

[228] Evett IW, Weir BS. *Interpreting DNA Evidence: Statistical Genetics for Forensic Scientists*. Sinauer Associates Inc,: Sunderland, MA, 1998. ; Kaye DH. The Expected Value Fallacy in State v. Wright. *Jurimetrics: The Journal of Law, Science, and Technology*. 2011; 51(4):1921082. doi:ssrn.com/abstract=1921082.

[229] Evett IW, Weir BS. *Interpreting DNA Evidence: Statistical Genetics for Forensic Scientists*. Sinauer Associates Inc,: Sunderland, MA, 1998. ; Kaye DH. The Expected Value Fallacy in State v. Wright. *Jurimetrics: The Journal of Law, Science, and Technology*. 2011; 51(4):1921082. doi:ssrn.com/abstract=1921082.

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purposes, taking a number that laypersons would have heard of, such as one billion, would seem to be sufficient to convey the idea of rarity.[230] There have been few publications on these matters, and more research is needed to understand (1) the implications of possible linkage disequilibrium for results with 24-locus kits, and (2) the impact of very high LRs (or small RMPs) on a layperson's understanding of DNA results.

Current understanding warrants an upper bound that is lower than the world population, and even lower still when the propositions consider first-degree relatives (i.e., parents, children, and siblings). FSSPs should communicate and justify their use of a reporting cap to end-users (see ***Appendix 5.1*** for sample language). For completeness, though not for presentation in court, if a computed number is above the cap, this number also should be made available in the case file.

Recommendation 4.3: To avoid presenting likelihood ratios that are larger than can be supported by currently available research and to assist in the comprehension of analyses that result in very large likelihood ratios (or very small Random Match Probabilities) with respect to unrelated individuals, forensic science service providers should implement a reporting cap of 1 billion (or 1 in 1 billion), or an alternative value that can be justified by research.*

* See footnote[231] for dissent.

4.3.6 Expressing LRs Less Than 1

When an LR is smaller than 1, it can be difficult for the end-user to understand which proposition the evidence supports. Instead of, or in addition to, presenting the LR number as a decimal or a fraction (e.g., 0.00001 or 1/100,000), one can reverse the propositions, inverting the LR value, to report an LR greater than 1.[232] If the FSSP chooses to only report the reversed propositions and inverted LR value, the non-inverted value must remain available in the case file. Clarity in reports that contain inverted LRs is especially important. The end-user may be used to seeing a typical order for the propositions (i.e., H_1: a POI is the source versus H_2: an unknown, unrelated individual is the source) and may not recognize when the propositions are reversed (i.e., H_2 versus H_1).

[230] Buckleton J, Bright JA, Taylor D. *Forensic DNA Evidence Interpretation*. 2nd ed. CRC Press: Boca Raton, 2016. doi:10.4324/9781315371115.

[231] Four EWG members did not support Recommendation 4.3, citing concerns that the proposed numerical threshold seems arbitrary without a clear basis in FSSPs' validation data. Further, they fear that the cap might unintentionally resemble a source attribution statement, leading non-scientists to interpret it as a definitive assertion of a Person of Interest's presence. The dissenters also argue that the proposed cap, intended to prevent bias, may underestimate DNA analysts' abilities to communicate the results or the factfinders' ability to understand the results, and hinder the transparency of information. Instead, the dissenters advocate for allowing factfinders to engage with the full information spectrum, emphasizing the need for further research on the appropriateness of a reporting cap in both number choice and laypeople's understanding.

[232] Marquis R, Biedermann A, Cadola L, Champod C, Gueissaz L, Massonnet G, Mazzella WD, Taroni F, Hicks T. Discussion on How to Implement a Verbal Scale in a Forensic Laboratory: Benefits, Pitfalls and Suggestions to Avoid Misunderstandings. *Science & Justice*. 2016; 56(5):364-70. doi:10.1016/j.scijus.2016.05.009.

In reports with RMP or **Combined Probability of Inclusion** (CPI) statistics, values were only reported to support an "inclusion." With LRs reported as quantifying support for a proposition consisting of only unknown individuals (so-called "exclusionary" propositions), the analyst must communicate the result clearly so that it is perceived to be different. For FSSPs that use qualitative statements of LRs (see ***Sec. 4.3.8*: Verbal Qualifier Statements Used to Supplement the LR**), the analyst likewise must ensure that results providing more support for H_2 versus H_1 are clearly distinguishable from results providing more support for H_1 than H_2.

Since these nuances or wording differences in a narrative report (see ***Sec. 5.4.1*: Narrative, Tabular, Lists, and Combined Report Formats**) can be easily overlooked, we recommend reporting *both* the LR less than 1 and the LR with the propositions reversed. For example, consider an LR of 0.005 (or 1/200) in which H_1 considers the POI and three unknown individuals and H_2 considers four unknown individuals without the POI. The following written statement alerts the end-user to the change, inverts the LR, and reverses the propositions with the goal of limiting the potential for misunderstanding:

> An LR of 1/200 was assigned. This LR indicates that the DNA results support the alternative proposition that only unknown individuals—and not a POI—contributed to the DNA mixture. Because numbers smaller than 1 are difficult to comprehend, this result can be restated as follows: It is 200 times more likely to observe the DNA results if four unknown individuals—and not the POI—are the origin of the DNA mixture from item X rather than if it is the POI and three unknown individuals.

In verbal communication and testimony, however, it may not be necessary to present both LRs as long as the order of propositions is explicit and clear to the end-user.

Recommendation 4.4: To make likelihood ratio values less than 1 (e.g., 0.00001 or 1/100,000) easier to comprehend, forensic science service providers can reverse the propositions, which will invert the LR (e.g., 100,000). If doing so, analysts must clearly report that they have reversed the propositions for this purpose. The original likelihood ratio must be available in the case file.

4.3.7 The "Match Form" Presentation of the LR

The LR is essentially a number that expresses how many times more probable the evidence is if one proposition is true than if another proposition is true, and that is how it usually is described

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in court. But some DNA experts prefer an alternative that has been called the "match form."[233] An example of a "match form" statement is that "[a] match between the shoes … and [the defendant] is 9.67 thousand times more probable than a coincidental match to an unrelated African-American person."[234] More generally, a match-form presentation states that "a match between the evidence and reference [samples] is (some number) times more probable than coincidence."[235]

This formulation has been criticized as highly misleading.[236] The main concern is that juxtaposing "match" and "coincidence" will lead judges and jurors to think that the "match statistic"[237] pertains to the probabilities of propositions about the source of the DNA. In simpler terms, the concern is that most people will understand "coincidence" and "coincidental match" as an assertion that the observed match is the result of coincidence; moreover, they will think that "match" is an assertion that the defendant (or other POI) is "the matcher."

We have located no human-factors or psychological research directed at the question of whether the "match form" is *more* prone to this misunderstanding than is the usual conditional-probability presentation.[238] Nonetheless, we believe that avoiding the transposition of the traditional probabilities in an LR requires special care if a match-versus-coincidence approach is to be used at all. The DNA expert must explain not only that a "DNA match" is merely a degree of similarity or alignment between the electropherograms (EPGs) being compared, but also that "coincidence" or "coincidental match" is shorthand for the proposition that the "match" is a match to an unrelated individual (or other specified source)—and that it is *not* a conclusion that a coincidence has occurred. Because "match form" testimony leans so heavily on the ambiguous

[233] Perlin MW. Explaining the Likelihood Ratio in DNA Mixture Interpretation. Presented at: Proceedings of Promega's Twenty First International Symposium on Human Identification; 2010; https://www.promega.com/~/media/files/resources/conference%20proceedings/ishi%2021/oral%20presentations/perlin.pdf?la=en ; Perlin MW, Kadane JB, Cotton RW. Match Likelihood Ratio for Uncertain Genotypes. *Law, Probability and Risk*. 2009; 8(3):289-302. doi:10.2139/ssrn.1509435.

[234] United States v. Anderson, No. 4:21-CR-00204, 2023 WL 3510823, at *3 (M.D. Pa. Apr. 26, 2023). For additional instances of "match form" testimony or reporting, see, for example, Howell v. Schweitzer, Case No. 1:20-cv-2853, 2023 WL 1785530 (N.D. Ohio Jan. 11, 2023); Sanford v. Russell, No. 17-13062, 2021 WL 1186495 (E.D. Mich. Mar. 30, 2021); State v. Anthony, 266 So.3d 415 (La. Ct. App. 2019).

[235] Perlin MW, Dormer K, Hornyak J, Schiermeier-Wood L, Greenspoon S. TrueAllele® Casework on Virginia DNA Mixture Evidence: Computer and Manual Interpretation in 72 Reported Criminal Cases. *PloS One*. 2014; 9(3):e92837. doi:10.1371/journal.pone.0092837.

[236] Thompson WC. Uncertainty in Probabilistic Genotyping of Low Template DNA: A Case Study Comparing STRMix™ and TrueAllele®. *Journal of Forensic Sciences*. 2023; 68(3):1049-63. doi:10.1111/1556-4029.15225.

[237] Perlin MW, Allan WP, Bracamontes JM, Danser KR, Legler MM. Reporting Exclusionary Results on Complex DNA Evidence, a Case Report Response to 'Uncertainty in Probabilistic Genotyping of Low Template DNA: A Case Study Comparing STRmix™ and Trueallele®' Software. 2023; doi:10.2139/ssrn.4449313.

[238] Misconstruing a computed LR as a statement about the probabilities of the hypotheses (propositions) concerning the source of the questioned sample involves equating probabilities of evidence conditional on hypotheses to probabilities of hypotheses conditional on the evidence. This unthinking reversal of the terms in a conditional probability is the transposition fallacy.

phrase “coincidental match” and has no clear benefit, we do not recommend its use for explaining a DNA LR.[239]

4.3.8 Verbal Qualifier Statements Used to Supplement the LR

The LR (as any statistic) can be difficult to comprehend in isolation regardless of the mode of presentation.[240] Therefore, the analyst may determine it is helpful—depending on the circumstances—to supplement the LR value with a verbal term. This verbal term is an adjective that describes the extent of support the findings provide for one proposition versus an alternative.[241] Before FSSPs choose to assign any such qualitative descriptors, they should be aware of the possible risk that end-users could misunderstand the intent or meaning of the words. To this end, there are several important human factors to consider.

A verbal expression *without* a statistical value might not capture what the expert means to communicate and may exacerbate any misunderstandings the factfinder may have.[242] For example, Martire et al. have found that end-users misinterpret “weak” or “limited” support for one proposition as support for the *alternative* proposition.[243] Thus, the propositions should still be clearly referenced in a verbal statement to help the end-user and factfinder correctly incorporate the information.[244] The verbal term should not serve as a substitute for the assigned value.

[239] Match-form testimony and reporting does not depend on any particular method or system for computing a likelihood ratio. In questioning the desirability of this manner of expressing the results, we are neither endorsing nor questioning the validity or utility of any probabilistic genotyping system. Rather, our remarks are limited to the human-factors issue of how to present valid and reliably computed LRs to participants in the criminal justice system.

[240] Martire KA, Kemp RI, Watkins I, Sayle MA, Newell BR. The Expression and Interpretation of Uncertain Forensic Science Evidence: Verbal Equivalence, Evidence Strength, and the Weak Evidence Effect. *Law and Human Behavior*. 2013; 37(3):197-207. doi:10.1037/lhb0000027.

[241] Evett IW. Bayesian Inference and Forensic Science: Problems and Perspectives. *Journal of the Royal Statistical Society: Series D (The Statistician)*. 1987; 36(2-3):99-105. doi:10.2307/2348502.

[242] Martire KA, Kemp RI, Sayle M, Newell BR. On the Interpretation of Likelihood Ratios in Forensic Science Evidence: Presentation Formats and the Weak Evidence Effect. *Forensic Science International*. 2014; 240:61-8. doi:10.1016/j.forsciint.2014.04.005; Martire KA, Kemp RI, Watkins I, Sayle MA, Newell BR. The Expression and Interpretation of Uncertain Forensic Science Evidence: Verbal Equivalence, Evidence Strength, and the Weak Evidence Effect. *Law and Human Behavior*. 2013; 37(3):197-207. doi:10.1037/lhb0000027; Martire KA, Watkins I. Perception Problems of the Verbal Scale: A Reanalysis and Application of a Membership Function Approach. *Science & Justice*. 2015; 55(4):264-73. doi:10.1016/j.scijus.2015.01.002; Mullen C, Spence D, Moxey L, Jamieson A. Perception Problems of the Verbal Scale. *Science & Justice*. 2014; 54(2):154-8. doi:10.1016/j.scijus.2013.10.004; Sjerps M, Biesheuvel DB. The Interpretation of Conventional and 'Bayesian' Verbal Scales for Expressing Expert Opinion: A Small Experiment among Jurists. *International Journal of Speech, Language and the Law*. 1999; 6(2):214-27. doi:10.1558/ijsll.v6i2.214.

[243] Martire KA, Kemp RI, Sayle M, Newell BR. On the Interpretation of Likelihood Ratios in Forensic Science Evidence: Presentation Formats and the Weak Evidence Effect. *Forensic Science International*. 2014; 240:61-8. doi:10.1016/j.forsciint.2014.04.005; Martire KA, Kemp RI, Watkins I, Sayle MA, Newell BR. The Expression and Interpretation of Uncertain Forensic Science Evidence: Verbal Equivalence, Evidence Strength, and the Weak Evidence Effect. *Law and Human Behavior*. 2013; 37(3):197-207. doi:10.1037/lhb0000027.

[244] Evett IW, Jackson G, Lambert JA, McCrossan S. The Impact of the Principles of Evidence Interpretation on the Structure and Content of Statements. *Science & Justice*. 2000; 40(4):233-9. doi:10.1016/S1355-0306(00)71993-9.

There are a variety of scales that attempt to provide a qualitative or verbal qualifier alongside a range of LRs (adapted in **Table 4.3**, **Table 4.4**, and **Table 4.5**).[245] The selection and use of these scales is a matter of convention. However, each scale considers LR values of approximately 1 in a similar fashion: that the results are *uninformative*, their value *null*, or the findings *equally probable given each of the propositions.*

An important point regarding the illustrative scales included in **Tables 4.3–4.5** is the absence of terms like *excluded* and *included*. These terms do not belong on a verbal scale because they imply categorical decisions. The LR reflects the extent of the support the results provide for one proposition rather than the other and not a categorical "conclusion."

Table 4.3: Verbal scale adapted from recommendations of the SWGDAM Ad Hoc Working Group on Genotyping Results Reported as LRs

LR for H_p Support and 1/LR for H_d Support	Verbal Qualifier
1	Uninformative
2 – 99	Limited Support
100 – 9,999	Moderate Support
10,000 – 999,999	Strong Support
≥ 1,000,000	Very Strong Support

Adapted from Recommendations of the SWGDAM Ad Hoc Working Group on Genotyping Results Reported as Likelihood Ratios.[246]

The Scientific Working Group on DNA Analysis Methods (SWGDAM) provides the following statement explanation:

> Likelihood ratios occur on a continuum; the categories recommended here have been chosen in part based on the observation that adventitious support for a proposition (e.g., LR >1 for an individual whose DNA is not present in the sample; or LR <1 for an individual whose DNA is present in the sample) is most commonly observed within the Limited Support category and generally not expected within the Very Strong Support category.[247]

[245] European Network of Forensic Science Institutes (ENFSI). *ENFSI Guideline for Evaluative Reporting in Forensic Science: Strengthening the Evaluation of Forensic Results across Europe (STEOFRAE), Version 3.0*. 2015. https://enfsi.eu/wp-content/uploads/2016/09/m1_guideline.pdf; Marquis R, Biedermann A, Cadola L, Champod C, Gueissaz L, Massonnet G, Mazzella WD, Taroni F, Hicks T. Discussion on How to Implement a Verbal Scale in a Forensic Laboratory: Benefits, Pitfalls and Suggestions to Avoid Misunderstandings. *Science & Justice*. 2016; 56(5):364-70. doi:10.1016/j.scijus.2016.05.009; Scientific Working Group on DNA Analysis Methods (SWGDAM). *Recommendations of the SWGDAM Ad Hoc Working Group on Genotyping Results Reported as Likelihood Ratios*. 2018. https://www.swgdam.org/_files/ugd/4344b0_dd5221694d1448588dcd0937738c9e46.pdf.

[246] Scientific Working Group on DNA Analysis Methods (SWGDAM). *Recommendations of the SWGDAM Ad Hoc Working Group on Genotyping Results Reported as Likelihood Ratios*. 2018. https://www.swgdam.org/_files/ugd/4344b0_dd5221694d1448588dcd0937738c9e46.pdf.

[247] Ibid., p. 3.

These verbal expressions attempt to give the end-user context regarding the LR value. However, in a given case, it is not possible to infer if the LR is "good," "bad," "sufficient," or not. It is for the factfinders to decide whether an LR of 10 is sufficient in the case. To understand the impact of the LR on the case, the factfinder needs to consider DNA results together with the other information within the case (e.g., non-DNA evidence, testimony).

Table 4.4 presents an example of a scale originally presented in Marquis et al.[248] In general, verbal scales are uniform in that each category or "bin" in the scale spans one order of magnitude. Mathematically, the scale is logarithmic. The log-LR expresses *the weight of evidence.*[249]

Each verbal communication should be read as "The results support the proposition that ... rather than the proposition that ..." followed by the level of support that corresponds to the LR.

Table 4.4: Marquis et al. (2016) proposed verbal scale for reporting the value of the scientific observations

LR	Verbal Communication
> 10,000	This support is qualified as *extremely strong.*
> 1000 – 10,000	This support is qualified as *very strong.*
> 100 – 1000	This support is qualified as *strong.*
> 10 – 100	This support is qualified as *moderate.*
> 1 – 10	This support is qualified as *weak* or *limited.*[250]
1	The results support neither proposition. This support is qualified as *null.*

Table adapted from: Marquis et al, 2016.[251]

Table 4.5 is adapted from an example provided in the *ENFSI Guideline for Evaluative Reporting*.[252] The scale provides two options for phrasing**.**

[248] Marquis R, Biedermann A, Cadola L, Champod C, Gueissaz L, Massonnet G, Mazzella WD, Taroni F, Hicks T. Discussion on How to Implement a Verbal Scale in a Forensic Laboratory: Benefits, Pitfalls and Suggestions to Avoid Misunderstandings. *Science & Justice*. 2016; 56(5):364-70. doi:10.1016/j.scijus.2016.05.009.

[249] Good IJ. *Probability and the Weighing of Evidence*. Charles Griffin & Company Limited: London, UK, 1950.

[250] To avoid the weak evidence effect, Marquis et al. (2016) suggest reporting in two steps. First, forensic scientists could state that the observations support a given proposition over the other. Then, in a second sentence, they would qualify this support as limited.

[251] Marquis R, Biedermann A, Cadola L, Champod C, Gueissaz L, Massonnet G, Mazzella WD, Taroni F, Hicks T. Discussion on How to Implement a Verbal Scale in a Forensic Laboratory: Benefits, Pitfalls and Suggestions to Avoid Misunderstandings. *Science & Justice*. 2016; 56(5):364-70. doi:10.1016/j.scijus.2016.05.009.

[252] European Network of Forensic Science Institutes (ENFSI). *ENFSI Guideline for Evaluative Reporting in Forensic Science: Strengthening the Evaluation of Forensic Results across Europe (STEOFRAE), Version 3.0*. 2015. https://enfsi.eu/wp-content/uploads/2016/09/m1_guideline.pdf.

Table 4.5: A verbal scale example presented in the *ENFSI Guideline for Evaluative Reporting*[253]

Values* of LR	Verbal Expression
1	The forensic findings do not support one proposition over the other. The forensic findings provide no assistance in addressing the issue.
2 – 10	The forensic findings provide weak support** for the first proposition relative to the alternative. The forensic findings are slightly more probable given one proposition relative to the other.
10 – 100	...provide moderate support for the first proposition rather than the alternative. …are more probable given …proposition ... than ...proposition ... .
100 – 1,000	...provide moderately strong support for the first proposition rather than the alternative. …are appreciably more probable given …proposition ... than ...proposition ... .
1,000 – 10,000	...provide strong support for the first proposition rather than the alternative. …are much more probable given …proposition ... than ...proposition ... .
10,000 – 1,000,000	...provide very strong support for the first proposition rather than the alternative. …are far more probable given …proposition ... than ...proposition ... .
1,000,000 and above	... provide extremely strong support for the first proposition rather than the alternative. … are exceedingly more probable given … proposition ... than ...proposition ... .

* LRs corresponding to the inverse (1/X) of these values (X) will express the degree of support for the specified alternative compared to the first proposition.

** Analysts or their reports should avoid conveying the impression that a statement of the kind "the forensic findings provide weak support for the first proposition compared to the alternative" is meaning that the findings provide support for the stated alternative. It just means that the findings are up to 10 times more probable if the first proposition is true than if the stated alternative is true. This is also the reason why the alternative should be explicitly stated. In cases where the reader could be misled as described above, forensic practitioners shall add additional comments.

If and when a verbal scale is used, the numerical LR should be stated before being translated into a qualitative expression.[254] Ideally, only one scale should be used for all types of analysis (e.g., autosomal DNA, Y-chromosome short tandem repeat [Y-STR], mitochondrial DNA [mtDNA]), propositions (e.g., sub-source-level, activity-level), and forensic-science disciplines. But using a common scale for all forensic-science disciplines will require coordination within and across standard-setting organizations.

Martire et al. found that a dual verbal-numerical scale that indicates the full range of numerical and verbal expressions led to an increase in the differentiation between the terms, an increase in the consistency of the interpretations of the terms, and an increase in the correspondence

[253] Ibid.

[254] ibid.; Scientific Working Group on DNA Analysis Methods (SWGDAM). *Recommendations of the SWGDAM Ad Hoc Working Group on Genotyping Results Reported as Likelihood Ratios*. 2018. https://www.swgdam.org/_files/ugd/4344b0_dd5221694d1448588dcd0937738c9e46.pdf.

with the experts' intentions.[255] McQuiston-Surrett and Saks emphasized that practitioners cannot just adopt a term and expect end-users to understand it.[256]

SWGDAM recommends reporting the full table for context.[257] However, Marquis et al. argue that providing the entire scale could be harmful because it invites a value assessment that incorporates comparison to the other terms on the scale rather than focusing on the LR.[258] That is, an LR of 1,000 has the same value regardless of where it fits on a scale. These conflicting views highlight the need to educate DNA analysts and end-users about ways to effectively communicate and understand the LR value.

In summary, if FSSPs use verbal terms to supplement the previously expressed LR value, they should be aware of the following:[259]

1. The use of verbal scales is merely a matter of choice, convention, or consensus.
2. If using a verbal scale, the same scale should be used across all forensic disciplines and all methods of analysis in all FSSPs. There should not be a special scale for DNA comparison results.
3. Verbal qualifiers are only applied *after* the numerical LR value is assigned. These terms should not stand alone or replace the communication of the LR value.
4. Verbal qualifiers should reference both propositions by conveying the *support* the DNA results provide for one proposition versus the other.
5. Whether written or spoken, qualitative LR scales only describe the support provided by the results. They do not express whether one proposition is more likely to be true than the other (see **Callout Box 6.3**).

[255] Martire KA, Kemp RI, Newell BR. The Psychology of Interpreting Expert Evaluative Opinions. *Australian Journal of Forensic Sciences*. 2013; 45(3):305-14. doi:10.1080/00450618.2013.784361.

[256] McQuiston-Surrett D, Saks MJ. Communicating Opinion Evidence in the Forensic Identification Sciences: Accuracy and Impact. *Hastings Law Journal*. 2008; 59(5):1159-90.

[257] Scientific Working Group on DNA Analysis Methods (SWGDAM). *Recommendations of the SWGDAM Ad Hoc Working Group on Genotyping Results Reported as Likelihood Ratios*. 2018. https://www.swgdam.org/_files/ugd/4344b0_dd5221694d1448588dcd0937738c9e46.pdf.

[258] Marquis R, Biedermann A, Cadola L, Champod C, Gueissaz L, Massonnet G, Mazzella WD, Taroni F, Hicks T. Discussion on How to Implement a Verbal Scale in a Forensic Laboratory: Benefits, Pitfalls and Suggestions to Avoid Misunderstandings. *Science & Justice*. 2016; 56(5):364-70. doi:10.1016/j.scijus.2016.05.009.

[259] European Network of Forensic Science Institutes (ENFSI). *ENFSI Guideline for Evaluative Reporting in Forensic Science: Strengthening the Evaluation of Forensic Results across Europe (STEOFRAE), Version 3.0*. 2015. https://enfsi.eu/wp-content/uploads/2016/09/m1_guideline.pdf; Evett IW, Jackson G, Lambert JA, McCrossan S. The Impact of the Principles of Evidence Interpretation on the Structure and Content of Statements. *Science & Justice*. 2000; 40(4):233-9. doi:10.1016/S1355-0306(00)71993-9; Gill P, Hicks T, Butler JM, Connolly E, Gusmao L, Kokshoorn B, Morling N, van Oorschot RAH, Parson W, Prinz M, Schneider PM, Sijen T, Taylor D. DNA Commission of the International Society for Forensic Genetics: Assessing the Value of Forensic Biological Evidence - Guidelines Highlighting the Importance of Propositions. Part II: Evaluation of Biological Traces Considering Activity Level Propositions. *Forensic Science International: Genetics*. 2020; 44:102186. doi:10.1016/j.fsigen.2019.102186; Gill P, Hicks T, Butler JM, Connolly E, Gusmao L, Kokshoorn B, Morling N, van Oorschot RAH, Parson W, Prinz M, Schneider PM, Sijen T, Taylor D. DNA Commission of the International Society for Forensic Genetics: Assessing the Value of Forensic Biological Evidence - Guidelines Highlighting the Importance of Propositions: Part I: Evaluation of DNA Profiling Comparisons Given (Sub-) Source Propositions. *Forensic Science International: Genetics*. 2018; 36:189-202. doi:10.1016/j.fsigen.2018.07.003; Marquis R, Biedermann A, Cadola L, Champod C, Gueissaz L, Massonnet G, Mazzella WD, Taroni F, Hicks T. Discussion on How to Implement a Verbal Scale in a Forensic Laboratory: Benefits, Pitfalls and Suggestions to Avoid Misunderstandings. *Science & Justice*. 2016; 56(5):364-70. doi:10.1016/j.scijus.2016.05.009.

6. The LR represents the value of the results; therefore, terms such as *exclusion* or *inclusion*, which are categorical opinions (i.e., a decision), should not be part of the scale.
7. Results are uninformative only when the reported LR is 1 or approximately 1 because this implies that the probability of the results given each proposition is approximately equal (see ***Sec. 4.5.3*: *Expressing LR Values of Approximately 1***). The term "uninformative" describes the inability of the DNA results to discriminate between the propositions. But informing the factfinder that DNA testing was undertaken and that it turned out to be useless in assessing the source propositions can be useful for a different purpose. If the judge or jury would anticipate DNA evidence, the prosecution may introduce the "uninformative" result just to show that the state conducted a thorough investigation and did not overlook potentially exculpatory evidence.
8. The scale should work in a comparable way for LRs less than 1 to reflect the extent of support the results provide for the second proposition versus the first.

4.4 Other Quantitative Expressions of DNA Results

The EWG advocates expressing DNA results quantitatively, using the LR to indicate the strength of the evidence. However, some FSSPs may not have the resources to implement this approach immediately. Furthermore, some use a hybrid manual and software approach, depending on sample quality and complexity.

4.4.1 Random Match Probability

The RMP represents the probability that an individual, selected at random from the population, will have a DNA profile with the same genotypes as the evidence DNA profile. It is most often calculated for single-source or deduced profiles, although Bille et al. have discussed applications for more complicated DNA mixtures.[260] The smaller the probability, the rarer it is to observe the DNA profile in the population of interest.

The RMP lacks balance because it does not consider two competing propositions. It does not evaluate the DNA results under the consideration that the POI is the source of the DNA, but only under the consideration that an unknown individual is the source of the DNA. Using the RMP as the measure of probative value implicitly assumes that the probability of the DNA results if the POI is the source of the DNA is 1, and this assumption is communicated to the end-user using a qualitative term (see ***Sec. 4.5*: *Qualitative Expressions of DNA Comparison Results***). However, only for a properly analyzed high-quality, single-source profile (i.e., a robust profile with peak heights with no expectation of drop-out) is the probability of the results if the POI is the source of the DNA approximately 1.

[260] Bille T, Bright JA, Buckleton J. Application of Random Match Probability Calculations to Mixed STR Profiles. *Journal of Forensic Sciences*. 2013; 58(2):474-85. doi:10.1111/1556-4029.12067.

In some instances, FSSPs may calculate a modified Random Match Probability (mRMP) when a DNA mixture profile has distinguishable component(s) as defined by FSSP protocol. The profile of an assumed known contributor may also be used to deduce a foreign component. Each deduced component is treated as if it were a single-source profile for statistical purposes. However, the mRMP restricts the potential genotypes to a subset of what is possible (using the peak heights, expected heterozygote peak height ratios, and mixture proportions). The procedure treats the discarded genotypes as having a probability of zero. This simplification can be especially dangerous when profiles are subject to stochastic effects in low-level data.[261]

4.4.2 Combined Probability of Inclusion

The *Combined Probability of Inclusion (CPI)*, also referred to as Random Man Not Excluded (RMNE), is the probability that, in a given population, a randomly selected, unrelated individual would be included as a potential contributor to the mixture profile. This approach is generally limited to DNA mixtures (or to loci within a mixture) in which allele drop-out is not suspected. The counterpart of CPI is the Combined Probability of Exclusion (CPE), which is simply 1 – CPI.

The initial appeal of the CPI approach was its simplicity and the fact that there was no need to assume the NOC present in a DNA mixture profile to perform the calculation. In addition, it was incorrectly considered to be a "conservative approach" because it allowed for all genotype combinations.[262] However, it has since fallen out of favor as a means of providing statistical weight to an evidence DNA profile since the CPI can only provide support for an inclusion.[263]

The primary criticism of the CPI is that it does not consider the DNA profile of the POI, it under-uses the data, and it is allele-centric rather than genotype-centric.[264] Typically, this statistical approach is used when the DNA mixture profile cannot be manually deconvolved into individual components. All genotype combinations are allowed despite peak height ratios that are inconsistent with expected DNA behavior and would otherwise be exculpatory. This approach, therefore, is not conservative for true non-contributors.[265]

[261] Buckleton J, Bright JA, Taylor D. *Forensic DNA Evidence Interpretation*. 2nd ed. CRC Press: Boca Raton, 2016. doi:10.4324/9781315371115.

[262] Ibid.

[263] Buckleton J, Curran J. A Discussion of the Merits of Random Man Not Excluded and Likelihood Ratios. *Forensic Science International: Genetics*. 2008; 2(4):343-8. doi:10.1016/j.fsigen.2008.05.005; Butler JM. *Advanced Topics in Forensic DNA Typing: Interpretation*. Elsevier Academic Press: San Diego, CA, 2014. ; Perlin MW. When Good DNA Goes Bad. *Journal of Forensic Research*. 2013; 04(01):S11. doi:10.4172/2157-7145.S11-003.

[264] Butler JM. *Advanced Topics in Forensic DNA Typing: Interpretation*. Elsevier Academic Press: San Diego, CA, 2014.

[265] Perlin MW. Inclusion Probability for DNA Mixtures Is a Subjective One-Sided Match Statistic Unrelated to Identification Information. *Journal of Pathology Informatics*. 2015; 6(1):59. doi:10.4103/2153-3539.168525.

The CPI approach is limited because if a profile, or a component of a profile, is low level, then the CPI statistic cannot be used at those loci where drop-out is suspected.[266] Again, omitting a locus can only be conservative when a locus has no exclusionary value.[267] In addition, there is a tendency for FSSPs to not fully appreciate the limitations of the CPI approach, such as the need for an empirically supported and appropriately applied stochastic threshold, as well as procedures that limit an analyst's ability to make determinations regarding loci suitability after evaluating the POI's DNA profile.[268] As a result, FSSPs may improperly implement this approach.[269]

FSSPs should move towards deconvolution methods, such as PGS, that make better use of all the data available in a DNA mixture profile (see ***Recommendation 4.1*** and ***Sec. 3.4.9: Deconvolution***).

4.5 Qualitative Expressions of DNA Comparison Results

FSSPs should use quantitative expressions of DNA results whenever possible. *Qualitative* expressions as a supplement to quantitative expressions can help to explain complex scientific results. However, FSSPs and analysts should be aware that some qualitative terminology can be confusing or misleading when used within a scientific paradigm. Qualitative terms to describe a DNA comparison are distinct from verbal qualifier statements presented in ***Sec. 4.3.8: Verbal Qualifier Statements Used to Supplement the LR***. However, some overlap does exist when LRs are approximately 1 and the term *uninformative* is used.

If an FSSP chooses to use qualitative terminology, it is important that each term is evaluated for its appropriateness, is explicitly defined, and is accompanied by a caveat explaining what the term does and does not mean.[270] Furthermore, if these terms are used, it is crucial that the analyst uses the terms in conjunction with the numerical value of the DNA comparison. The focus of DNA comparison results should generally rest on the expressed quantitative value except, possibly, when reporting exclusions (see ***Sec. 4.5.4: Exclusion Language***) or in limited circumstances such as a single-source female profile obtained from vaginal swab and the profile

[266] Budowle B, Onorato AJ, Callaghan TF, Della Manna A, Gross AM, Guerrieri RA, Luttman JC, McClure DL. Mixture Interpretation: Defining the Relevant Features for Guidelines for the Assessment of Mixed DNA Profiles in Forensic Casework. *Journal of Forensic Sciences*. 2009; 54(4):810-21. doi:10.1111/j.1556-4029.2009.01046.x.

[267] Curran JM, Buckleton J. Inclusion Probabilities and Dropout. *Journal of Forensic Sciences*. 2010; 55(5):1171-3. doi:10.1111/j.1556-4029.2010.01446.x.

[268] Bieber FR, Buckleton J, Budowle B, Butler JM, Coble MD. Evaluation of Forensic DNA Mixture Evidence: Protocol for Evaluation, Interpretation, and Statistical Calculations Using the Combined Probability of Inclusion. *BMC Genetics*. 2016; 17(1):125. doi:10.1186/s12863-016-0429-7.

[269] Butler JM, Kline MC, Coble MD. NIST Interlaboratory Studies Involving DNA Mixtures (MIX05 and MIX13): Variation Observed and Lessons Learned. *Forensic Science International: Genetics*. 2018; 37:81-94. doi:10.1016/j.fsigen.2018.07.024.

[270] National Commission on Forensic Science. *Views of the Commission Inconsistent Terminology*. 2015. https://www.justice.gov/archives/ncfs/page/file/1004446/download.

is consistent with intimate sample donor. See also ***Sec. 4.5.5: Qualitative Expressions of DNA Results with No Accompanying Statistic.***

All FSSPs should strive to use the same language to allow for consistency of communication with all criminal justice partners. This goal of uniformity may also help in other areas such as the training of examiners to ensure that everyone understands, uses, and defines the terms in the same way. FSSPs should then work with criminal justice partners to promote a shared understanding of the terminology used.

The following sections consider the use and misuse of qualitative expressions of DNA results.

4.5.1 Match Language

The use of terms such as match, identification, and individualization in forensic science has evolved.[271] Historically, the term "match" was used to indicate a positive identification between two samples.[272] Using this term without considerable explanation or qualification may be misunderstood to indicate that the samples originated from the same source. These categorical terms should be phased out in favor of terms that reflect the probabilistic nature of forensic science and the limitations of current technologies. While analysts may be able to state there are no observable differences when comparing two samples or items (e.g., forensic profile and POI profile), such testimony can falsely suggest that the degree of similarity in and of itself is meaningful.[273]

Alternative terms to "match" for expressing similarity between the profile of the evidence and a POI are *included, consistent with*, and *cannot be excluded (*or *cannot be ruled out), compatible*, or ***aligns** with*. Over time, these terms may become synonymous with the term *match* and may be misunderstood by the end-user as a source attribution.[274] Furthermore, using these terms in isolation, without a statistic or caveat, is potentially problematic.

For FSSPs using a hybrid manual and software approach for interpretation, confusion can arise when an analyst cannot initially manually assess an *exclusion* but the software output indicates (very strong) support for the proposition that the POI is *not* a contributor. In this situation, the phrase *cannot be excluded* may be confusing (see **Callout Box 4.1**).

[271] Cole SA. Forensics without Uniqueness, Conclusions without Individualization: The New Epistemology of Forensic Identification. *Law, Probability and Risk*. 2009; 8(3):233-55. doi:10.1093/lpr/mgp016; Kaye DH. Identification, Individualization and Uniqueness: What's the Difference? *Law, Probability and Risk*. 2009; 8(2):85-94. doi:10.1093/lpr/mgp018; Saks MJ, Koehler JJ. The Coming Paradigm Shift in Forensic Identification Science. *Science*. 2005; 309(5736):892-5. doi:10.1126/science.1111565.

[272] Biedermann A. The Strange Persistence of (Source) "Identification" Claims in Forensic Literature through Descriptivism, Diagnosticism and Machinism. *Forensic Science International: Synergy*. 2022; 4:100222. doi:doi:10.1016/j.fsisyn.2022.100222.

[273] Hicks T, Biedermann A, de Koeijer JA, Taroni F, Champod C, Evett IW. The Importance of Distinguishing Information from Evidence/Observations When Formulating Propositions. *Science & Justice*. 2015; 55(6):520-5. doi:10.1016/j.scijus.2015.06.008.

[274] Evett IW, Jackson G, Lambert JA, McCrossan S. The Impact of the Principles of Evidence Interpretation on the Structure and Content of Statements. *Science & Justice*. 2000; 40(4):233-9. doi:10.1016/S1355-0306(00)71993-9.

Callout Box 4.1: An Example of a Misleading Use of "Cannot Be Excluded"

The use of *cannot-be-excluded* terminology can confuse or mislead the end-user. The phrase is often associated with *included*. The end-user may not understand that the LR value indicates the opposite--the results can support the alternative proposition that two unknown individuals, not John Smith, are the contributors rather than John Smith and an unknown individual are.

Item	Item Description	Misleading Comparison Outcome	LR
1	Swab of door handle	John Smith **cannot be excluded** as a possible contributor	The results are of the order of 10,000 times more probable if two unknown individuals are the source of the DNA mixture than if John Smith and one unknown individual are.

Refer to ***Sec. 4.3.6*: Expressing LRs Less Than 1** for examples of how to report LR values less than 1 that require reversing the propositions.

A modifier such as *a possible contributor* used to supplement the term *included* or *excluded* may convey to the end-user that there is a *degree* to the comparison rather than a definitive conclusion. These terms would only be acceptable if they were complemented by a quantitative evaluation of the DNA comparison. However, manual methods are ill-equipped to provide this value, but if FSSPs continue to use the categorical phrases, they should consider supplemental report information to communicate the limitations to end-users (see ***Appendix 5.1***).

Although PGS and LRs obviate the need for categorical decisions, some FSSPs that have transitioned to probabilistic methods continue to use some of the qualitative terms. This practice may be a function of a "manual method carryover." Analysts and criminal justice partners are used to hearing terms such as *included* to convey the similarities between the evidence DNA profile and the DNA profile of a POI, and so FSSPs continue to use them. FSSPs that continue to use included-excluded terms with both manual and probabilistic methods exemplify this carryover.

The Department of Justice (DOJ) Uniform Language for Testimony and Reports (ULTR) considers the terms *support for inclusion*, *support for exclusion*, *exclusion*, and *uninformative* acceptable when referring to DNA examinations using PGS.[275] Presented in isolation, terms like *support for inclusion* and *support for exclusion* could be problematic because they do not reference both propositions. However, they are more appropriate when presented alongside the LR.

[275] United States Department of Justice. *Uniform Language for Testimony and Reports for Forensic Autosomal DNA Examinations Using Probabilistic Genotyping Systems*. 2022. https://www.justice.gov/olp/page/file/1095961/dl.

4.5.2 Issues with the Term "Inconclusive"

An analyst performing manual comparisons may not be able to reach an opinion regarding whether an individual could be included or excluded as a possible contributor of DNA. The common term of choice to describe this outcome is *inconclusive*. In place of *inconclusive*, and since a reason must be expressed for an opinion of this nature,[276] FSSPs still performing manual comparisons should state that:

> Due to the [reason: complexity, minimal nature] of the DNA profile, no opinion can be drawn regarding whether the POI is a possible contributor to the DNA or not.

To complicate matters, *inconclusive* is used to describe DNA results in several other contexts. For example, some FSSPs use *inconclusive* to describe uninterpretable results or determinations about the suitability of a DNA profile for comparisons. Some FSSPs use *inconclusive* to describe profiles that have been impacted by contamination or laboratory processing errors. We recommend describing the DNA profile as being suitable for comparison purposes or not, or as contaminated or compromised, rather than stating that the examination is *inconclusive*.

The range in which the term *inconclusive* is applied in the context of PGS and assigned LRs varies widely among FSSPs.[277] After the implementation of PGS, many FSSPs expanded the use of the term *inconclusive* to describe a range of LR values around 1 in which false inclusions or false exclusions were observed during validation studies.[278] However, this is not how validation studies should be used; the value of the DNA results should be considered along with other elements of the case. Using *inconclusive* detracts from the value of the DNA comparison, which should be expressed quantitatively.

An analyst describing a result as inconclusive could be seen as "deciding not to decide."[279] Analysts may see "inconclusive" as a cautious option compared to statements that the results provide limited support for one proposition compared to the alternative. But this reasoning may be misguided in some cases. We recommend analysts and FSSPs avoid using the term *inconclusive* and instead either describe the reasons why an examination is inconclusive or report the LR as a reflection of the value of the DNA comparison.

[276] ANSI National Accreditation Board (ANAB). *AR 3125: Accreditation Requirements for Forensic Testing and Calibration (2023)*. 2023. https://anab.qualtraxcloud.com/ShowDocument.aspx?ID=12371.

[277] Brinkac LM, Richetelli N, Davoren JM, Bever RA, Hicklin RA. DNAmix 2021: Laboratory Policies, Procedures, and Casework Scenarios Summary and Dataset. *Data Brief*. 2023; 48:109150. doi:10.1016/j.dib.2023.109150.

[278] This will be impacted by the choice of propositions.

[279] Dror IE, Langenburg G. "Cannot Decide": The Fine Line Between Appropriate Inconclusive Determinations Versus Unjustifiably Deciding Not to Decide. *Journal of Forensic Sciences*. 2019; 64(1):10-5. doi:10.1111/1556-4029.13854.

4.5.3 Expressing LR Values of Approximately 1

An LR of approximately 1 means that the DNA results provide equal support for both propositions. Rather than characterizing these results as *inconclusive,* LRs of approximately 1 can be described as *uninformative*, *neutral*, or *null*.[280] FSSPs using these terms should limit their use to LRs within a predefined, small range around 1 (such as 0.5 to 1.9).[281]

Importantly, the terms *uninformative*, *neutral*, or *null* do not convey that the LR itself is uninformative; rather an LR near 1 indicates that the DNA results cannot be of much assistance in discriminating between the propositions considered. We recommend the following phrases to express an LR of approximately 1 in addition to those listed in ***Sec. 4.3.8*: Verbal Qualifier Statements Used to Supplement the LR**:

- *The DNA results provide equal support for propositions 1 and 2.*
- *The DNA results are just as likely to be observed if [proposition 1] than if [proposition 2]. Therefore, they do not help discriminate between these propositions.*

4.5.4 Exclusion Language

A DNA analyst who makes a visual assessment that a POI profile does not share the same genotypes as the forensic profile will report the comparison as an "exclusion." From a purely mathematical and LR framework perspective, the numerical extent of support the results provide for one proposition versus the other should be communicated to the end-user rather than the categorical term. From a practical perspective, however, reporting an *exclusion* could be an exception to the rule of reporting in only quantitative terms. For example, stating *John Smith is excluded as a possible contributor of DNA* is easier to understand than *The DNA results are of the order of one million times more probable if three unknown individuals are the source of the DNA profile, rather than if John Smith and two unknown individuals are*.

Figure 4.1 presents an example of an "obvious" difference in profiles where the DNA analyst should be able to manually exclude the POI as a contributor to the questioned profile. The DNA has been assigned as coming from a single person; the quantity of DNA is sufficient to assume that allelic drop-out has not occurred; and the questioned profile is 14, 15 for the D2S441 locus and 15, 16 for D3S1358. If the POI profile was, for example, 12, 13 for the D2S441 locus and 14, 16 for D3S1358, then expressing exclusion is defensible.

[280] Scientific Working Group on DNA Analysis Methods (SWGDAM). *Recommendations of the SWGDAM Ad Hoc Working Group on Genotyping Results Reported as Likelihood Ratios*. 2018. https://www.swgdam.org/_files/ugd/4344b0_dd5221694d1448588dcd0937738c9e46.pdf.

[281] There is some consensus regarding the labeling of LRs of 1 as being uninformative. Catoggio D, Bunford J, Taylor D, Wevers G, Ballantyne KN, Morgan R. An Introductory Guide to Evaluative Reporting in Forensic Science. *Australian Journal of Forensic Sciences*. 2019; 51(sup1):S247-51. doi:10.1080/00450618.2019.1568560; Scientific Working Group on DNA Analysis Methods (SWGDAM). *Recommendations of the SWGDAM Ad Hoc Working Group on Genotyping Results Reported as Likelihood Ratios*. 2018. https://www.swgdam.org/_files/ugd/4344b0_dd5221694d1448588dcd0937738c9e46.pdf.

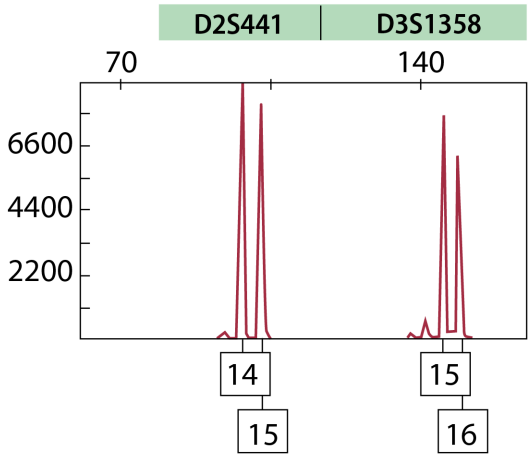

Figure 4.1: Example of a single source questioned profile.

Guidance provided by ENFSI in the *Best Practice Manual for Human Forensic Biology and DNA Profiling* distinguishes the use of exclusions during investigative and evaluative phases.[282] Exclusions are practical during the investigative phase because if there is an incompatibility between the evidence profile and a POI profile, for example, with possible DNA database candidates, then this lead is usually not followed.

Reporting an exclusion instead of a complex statistic may be particularly beneficial in a report containing numerous items and comparisons. FSSPs would need to set a threshold for the LR value that allows this.[283] An alternative is to invert ratios less than 1 (see ***Sec. 4.3.6*: *Expressing LRs Less Than 1***).

Although the categorical term *exclusion* may help the end-user or factfinder understand the result more easily, its use is not without risk. For example, it will not always be beneficial to the POIs involved. A simple example is one with two defendants where the exclusion of person A may be more inculpatory for person B than if the numerical value for the weight of the evidence against person A was presented.

In some cases, the *absence* of a POI's DNA (inferred based on an exclusion) may have an impact on the case. The factfinder should be informed that the meaning of the possible absence of DNA cannot be assessed based solely on the DNA comparison, as discerning the meaning would require taking DNA transfer, persistence, and recovery into account (see **Callout Box 7.1**).

[282] European Network of Forensic Science Institutes (ENFSI). *Best Practice Manual for Human Forensic Biology and DNA Profiling ENFSI-DNA-Bpm-03, Version 01*. 2022. https://enfsi.eu/wp-content/uploads/2022/12/ENFSI-DNA-BPM-03.pdf.

[283] Scientific Working Group on DNA Analysis Methods (SWGDAM). *Recommendations of the SWGDAM Ad Hoc Working Group on Genotyping Results Reported as Likelihood Ratios*. 2018. https://www.swgdam.org/_files/ugd/4344b0_dd5221694d1448588dcd0937738c9e46.pdf.

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Reported exclusions should be accompanied by an admonition not to overinterpret the result. The ENFSI manual recommends that, if using PGS or if the (exclusion) result is presented in court, the LR should be reported, even if it is smaller than 1.[284] SWGDAM allows for reporting *exclusions* with LRs: "[a] laboratory may establish a likelihood ratio value below which an individual may be excluded as a possible contributor rather than reporting a likelihood value that supports the defense proposition."[285]

If an FSSP chooses to use *excluded* in place of an LR, the assigned NOC and the propositions the DNA analyst considered should still be reported. For transparency, FSSPs should disclose the following information when reporting *exclusions*:

- Whether the *exclusion* was manually or probabilistically assessed if there is an option to use both approaches.
- The threshold used for determining an *exclusion* when using PGS.
- If an LR was assigned to decide an *exclusion*, that this value is present in the case record and can be provided upon request.
- Limitations related to *exclusions* that assist in the comprehension of the DNA results especially if the absence of DNA could be important in the case (see ***Appendix 5.1***).

Recommendation 4.5: DNA analysts should state the likelihood ratio value rather than using qualitative terms that end-users can misunderstand, such as "match," "included," "consistent with," and "cannot be excluded." It is acceptable to use the term "excluded" if the DNA analyst is transparent about how they reached that opinion and outlines the limitations of such an opinion.

4.5.5 Qualitative Expressions of DNA Results with No Accompanying Statistic

There may be instances where analysts (whether using manual or probabilistic interpretation) describe a comparison using only qualitative terminology. A common example is a comparison between two or more unknown samples to provide *investigative* information to the end-user. In these situations, the EWG recommends using terminology such as *included as a possible contributor* rather than *match*.

[284] European Network of Forensic Science Institutes (ENFSI). *Best Practice Manual for Human Forensic Biology and DNA Profiling ENFSI-DNA-Bpm-03, Version 01*. 2022. https://enfsi.eu/wp-content/uploads/2022/12/ENFSI-DNA-BPM-03.pdf.

[285] Scientific Working Group on DNA Analysis Methods (SWGDAM). *Recommendations of the SWGDAM Ad Hoc Working Group on Genotyping Results Reported as Likelihood Ratios*. 2018. https://www.swgdam.org/_files/ugd/4344b0_dd5221694d1448588dcd0937738c9e46.pdf., p. 4, Recommendation 2.1.

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Other circumstances where FSSPs use language to convey similarity without an accompanying statistic should be limited. Though the Federal Bureau of Investigation's Quality Assurance Standards (FBI QAS) allows for a qualitative conveyance of the DNA comparison to support an inclusion in a casework report,[286] this practice should be restricted to cases where the source of the DNA is unlikely to be disputed (e.g., DNA aligns with the person from whom the intimate swab was taken).[287]

If case information gathered through case assessment prior to testing indicates that an association may be expected (e.g., complainant in sexual assault case), it would be better to condition on that individual (see ***Sec. 3.4.8*: *Conditioning***) than to report a qualitative comparison with no supporting statistic. Conditioning can be done whether using binary or probabilistic methods. If the case information is unclear, it may be more helpful to assign a quantitative value to the DNA comparison, underlining that the analyst understood that the issue of interest was whether the person was the source of the DNA. Should this not be the case, a new evaluation may be needed.

4.5.6 Terms Used to Describe Uncontested Information or Assumptions

Terms such as *assumed*, *not at issue*, and *conditioned* describe situations where it is reasonable to presume that no one would dispute that (for that given comparison) an individual was a contributor to the DNA.[288] This individual will be an assumed contributor given both propositions, which assists with the deconvolution of the profile. The propositions should be initially formed using case circumstances and not led by the findings; however, the propositions may need to be refined after the results are obtained.[289]

Typical examples of these situations are intimate items or an individual's property (see ***Sec. 4.3.1*: *Conditioning Information and Formulating Propositions***). It is the opinion of the EWG that the terms *assumed*, *not at issue*, and *conditioned* are acceptable qualitative expressions because these terms speak to the process of case assessment and interpretation rather than to an interpretation result. If the information changes and the assumption is no longer acceptable,

[286] Federal Bureau of Investigation (FBI). *Quality Assurance Standards for Forensic DNA Testing Laboratories*. 2020. https://le.fbi.gov/file-repository/forensic-qas-070120.pdf/view. Standard 11.2.6: A quantitative or qualitative statement to support all inclusions.

[287] Ibid. Standard 9.10.2: Performing statistical analysis in support of any inclusion that is determined to be relevant in the context of the case.

[288] Gill P, Hicks T, Butler JM, Connolly E, Gusmao L, Kokshoorn B, Morling N, van Oorschot RAH, Parson W, Prinz M, Schneider PM, Sijen T, Taylor D. DNA Commission of the International Society for Forensic Genetics: Assessing the Value of Forensic Biological Evidence - Guidelines Highlighting the Importance of Propositions: Part I: Evaluation of DNA Profiling Comparisons Given (Sub-) Source Propositions. *Forensic Science International: Genetics*. 2018; 36:189-202. doi:10.1016/j.fsigen.2018.07.003.

[289] Buckleton J, Taylor D, Bright JA, Hicks T, Curran JM. When Evaluating DNA Evidence within a Likelihood Ratio Framework, Should the Propositions Be Exhaustive? *Forensic Science International: Genetics*. 2021; 50:102406. doi:10.1016/j.fsigen.2020.102406; Hicks T, Biedermann A, de Koeijer JA, Taroni F, Champod C, Evett IW. The Importance of Distinguishing Information from Evidence/Observations When Formulating Propositions. *Science & Justice*. 2015; 55(6):520-5. doi:10.1016/j.scijus.2015.06.008.

then the evaluation can be performed given a new pair of propositions, and end-users should be informed that the analyst can perform a new evaluation.

4.6 Interpretation and Expression of Serological Screening Results

Although the EWG was tasked to review human factors in autosomal short tandem repeat (STR) DNA analysis, we would be remiss to not also mention human factors considerations in the interpretation and expression of serology results that often accompany DNA testing. Serological examinations seek to provide information about the potential presence or absence of biological material as well as the nature of that material (e.g., blood, semen, saliva).

The results of these tests not only may impact the direction of subsequent DNA testing but also may provide guidance during an investigation. For example, the possible presence of blood on a knife collected from a scene where someone was stabbed may guide an investigator's hypothesis about the relevance of the item to the case (see ***Sec. 5.3.2.4: Possible Explanations for DNA Results***).

Serological testing may vary among FSSPs. FSSP management's decision, which may be informed by cost and availability of resources, to procure and validate certain tests will dictate which testing methods are available to the analyst. Because DNA testing alone may not suffice to address case-relevant issues, serology testing may also be needed. The analyst needs to determine, either on a case-by-case basis or according to the standard operating procedure (SOP) of the FSSP, whether they can offer opinions on the serology results.

In the case of sexual assault kits (SAKs), many FSSPs have moved away from microscopic sperm cell searches and other testing to Direct-to-DNA male screening workflows.[290] This approach, while increasing efficiency and reducing sample consumption, does not provide information on the nature of the biological material. Such information may be important even in instances where the source of the DNA is not. Additionally, some FSSPs may never perform serological testing, and among those that do, the methods and language used to express the results can differ.

The value of the test results and the limitations of a given test are determined by the method used, the validation results, and the implementation of the procedure. However, like all human endeavors, these and other aspects of DNA analysis are affected by human factors and can be subject to cognitive bias. Opinions regarding the presence or absence of a cell type or biological material will be based, in part, on contextual information. Clear SOPs and other procedures (e.g., peer review) should be in place to safeguard the interpretation of test results against cognitive bias (see ***Sec. 8.4: Internal Review***).

[290] Scientific Working Group on DNA Analysis Methods (SWGDAM). *Report on Y-Screening of Sexual Assault Evidence Kits (SAEKs)*. 2020. https://www.swgdam.org/_files/ugd/4344b0_e8334cb799704a1dabbd8d41f58b979d.pdf.

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All serology methods have well-known limitations.[291] For example, tests designed to detect one biological material (e.g., blood) may yield positive results with other materials (such as semen, urine, and saliva).[292] In the detection of prostate-specific antigen (PSA, also known as p30) testing, positive results have been associated with semen-free vaginal samples[293] and oral swabs after ingesting energy drinks.[294]

Conversely, all testing methods have limits of sensitivity that vary depending on the preparation of the testing chemicals and the way in which the test is performed. Therefore, it is critical for FSSPs to understand false positive and false negative rates in screening tests.

4.6.1 Interpreting and Recording Test Results

Although there are new techniques that promise to resolve biological material types,[295] many of the technologies[296] in use today require an analyst to categorize the result by visual inspection.[297] Test results may take the form of a color change or require certain characteristics to be classified either morphologically (e.g., sperm heads) or ordinally (e.g., a high or low density of cells). For example, an acid phosphatase (AP) test for seminal fluid relies on the development of a purple color (or other color depending on the AP test used) to indicate a positive result.

The length of time needed for the color to develop, and the intensity of the color, depend on the nature of the stain. A color change may be recorded in the analyst's notes, on a worksheet, or photographically. The results are typically characterized as either negative, positive, or weakly positive if the change occurred slowly or is faint (in accordance with the FSSP's validation).

[291] Petersen D, Kovacs F. Phenolphthalein False-Positive Reactions from Legume Root Nodules. *Journal of Forensic Sciences*. 2014; 59(2):481-4. doi:10.1111/1556-4029.12352; Ricci U, Carboni I, Torricelli F. False-Positive Results with Amylase Testing of Citrus Fruits. *Journal of Forensic Sciences*. 2014; 59(5):1410-2. doi:10.1111/1556-4029.12457; SERATEC. *PSA in Body Fluids: An Overview for Users of the SERATEC® PSA SEMIQUANT Tests*. Germany. 2011. https://www.seratec.com/docs/user_instructions/psa_in_body_fluids.

[292] Horjan I, Barbaric L, Mrsic G. Applicability of Three Commercially Available Kits for Forensic Identification of Blood Stains. *Journal of Forensic and Legal Medicine*. 2016; 38:101-5. doi:10.1016/j.jflm.2015.11.021.

[293] Denison SJ, Lopes EM, D'Costa L, Newman JC. Positive Prostate-Specific Antigen (PSA) Results in Semen-Free Samples. *Canadian Society of Forensic Science Journal*. 2004; 37(4):197-206. doi:10.1080/00085030.2004.10757576.

[294] DiFrancesco J, Sutton J. Re-Evaluation of the Seratec® PSA Semiquant Test: Comparison of Kit Provided Buffer with Phosphate Buffer Saline. *Canadian Society of Forensic Science Journal*. 2015; 48(3):137-51. doi:10.1080/00085030.2015.1051315.

[295] Sijen T. Molecular Approaches for Forensic Cell Type Identification: On mRNA, miRNA, DNA Methylation and Microbial Markers. *Forensic Science International: Genetics*. 2015; 18:21-32. doi:10.1016/j.fsigen.2014.11.015.

[296] Different types of tests are available that may assist in determining the biological nature of a trace. Chemical tests (e.g., KM test for blood), enzymatic tests (e.g., amylase test for saliva), and immunological tests (e.g., ABAcard p30 for seminal fluid) are used by many FSSPs and are often commercially available. Other test types, such as DNA-based methods (e.g., methylation testing), RNA-based methods (e.g., mRNA, piRNA), or those based on microbiomes, are less commonly used. Mass spectrometry-based proteomics could be used to help screen for a number of peptides for each biological material. A discovery study is available at Butler ER, Yang H, Perez T, Almubarak I, Zapata J, Bakshi H, Sutherland M, Siegel D. The Development and Validation of a Multiple Reaction Monitoring (MRM) Mass Spectrometry (MS) Assay for Confident Identification of Protein Biomarkers for Blood, Semen, and Saliva. 73rd AAFS Annual Scientific Meeting, Virtual American Academy of Forensic Sciences, 2021. https://www.aafs.org/sites/default/files/media/documents/AAFS-2021-B6.pdf.

[297] Card-based serological testing methods such as Rapid Stain Identification of Human Saliva™, ABAcard® HemaTrace™, or SERATEC® PSA Semiquant™ also rely on the visualization of a colored band to indicate a positive test result.

Test results are often visualized and recorded by the primary analyst performing the test and not captured photographically. Challenges exist to photographing and producing an accurate representation of the results of color tests. In casework, photographing serological test results is often not practical, as these tests may be performed numerous times throughout the examination of evidence. These tests are also designed to be visualized at a set time point; a later photograph may not record the color observed at the relevant time. Stopping after each test would be cumbersome, time consuming, and require the additional manipulation of camera equipment. A potential exception is serological tests that are not time sensitive, such as a microscopic examination for sperm cells. With this technique, photography assists not only in the documentation, but also in peer review of the initial analyst's notes and conclusions.

Additional handling between evidence and photography equipment could also increase the risk of contamination as the camera may be mounted and connected to a computer system that requires user input via a keyboard. Additionally, lighting and other conditions can affect how accurately a photograph represents the object being photographed. This is especially true when the band on a test strip indicating a positive result is faint.

Although photographs are now typically retained digitally, some FSSPs may only maintain paper-based case files, and a printed photograph may not accurately reflect such a test result. If the analyst later provides a copy of the case file for external review, the photocopied version may deviate even further from what the analyst observed.

The data necessary to make a visual characterization are not always clear. For example, during the microscopic examination of a sample for the presence of sperm cells, it is possible to misidentify a sperm cell since other commonly encountered cells may mimic its appearance (e.g., yeast cells). Thus, observations of serology tests are subject to inter- and intra-observer variability, bias, and error.

The potential for bias and error may increase from lack of training and expertise or if the analyst is fatigued or under pressure. Conferring with a second analyst may reduce the possibility of mischaracterization; however, confirmation bias may also occur unless a blinded second analysis or slide review is routinely performed. Although an independent, blind analysis may reduce bias, this approach is not always practical or efficient for serology test methods and may require additional evidence consumption (see ***Sec. 8.5: Blinded Reviews***).

4.6.2 Limitations in Language Used to Express Serology Results

There are two main ways that vendors and FSSPs have historically categorized serological tests: *confirmatory* or *presumptive*; however, we recommend against their continued use since the terms are misleading. *Confirmatory* tests have been previously described for "the conclusive

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identification of a biological fluid."[298] *Presumptive* tests have been previously defined as tests that are used to express to the end-user that, if a positive result is obtained, that result indicates the *possible* presence of the biological material of interest, while a negative result indicates that the biological material of interest was not detected but does not confirm its absence.[299]

Test results are generally expressed using binary language such as yes/positive or no/negative; however, if the test is categorized as "confirmatory," the results may be expressed as an *identification* or *confirmation* of the biological material. Statements that are not accompanied by an explanation of what the results mean, or a limitations statement, run the risk of being misleading. For example:

- "Blood was identified on Item X."
- "Semen was identified on Item X."

The use of phrases regarding a test's ability to *identify* or *confirm* a biological material implies a level of certainty that the testing methods cannot support while also ignoring the potential for false positives and false negatives. That is, these terms do not adequately communicate the uncertainty that accompanies the test result. As such, end-users and factfinders may understand such language as communicating a factual statement about the presence or absence of a biological material rather than a probabilistic result.[300] To help resolve this issue, FSSPs should phase out categorial terms such as confirmed and identified, including *presumptive*/*presumed.* Terminology such as *indicates*/*indicative* better reflects the uncertainty that should be associated with the test results.

4.6.2.1 "Inconclusive" Serology Test Results

When performing binary interpretations of serology results, the testing results are not always clearly in support of one proposition (e.g., blood is present on this item) versus the other proposition (e.g., blood is not present on this item). Therefore, the analyst should provide an explanation of their opinion that it is not possible to provide information about the presence or absence of biological material in this instance.

[298] Organization of Scientific Area Committees (OSAC). *Standard for Use of Serological Testing Methods Associated with Forensic Investigations, Version 2.0. OSAC Proposed Standard 2021-S-0028*. 2022. https://www.nist.gov/system/files/documents/2022/10/31/OSAC%202021-S-0028%20Standard%20Use%20of%20Serological%20Testing%20Methods_REGISTRY%20VERSION.pdf. p. 2.

[299] Ibid. p. 3.

[300] European Network of Forensic Science Institutes (ENFSI). *Best Practice Manual for Human Forensic Biology and DNA Profiling ENFSI-DNA-Bpm-03, Version 01*. 2022. https://enfsi.eu/wp-content/uploads/2022/12/ENFSI-DNA-BPM-03.pdf; McQuiston-Surrett D, Saks MJ. Communicating Opinion Evidence in the Forensic Identification Sciences: Accuracy and Impact. *Hastings Law Journal*. 2008; 59(5):1159-90. ; McQuiston-Surrett D, Saks MJ. The Testimony of Forensic Identification Science: What Expert Witnesses Say and What Factfinders Hear. *Law and Human Behavior*. 2009; 33(5):436-53. doi:10.1007/s10979-008-9169-1.

Rather than expressing the test result as *inconclusive*, the analyst should indicate that no opinion was reached about the nature of the biological material, along with the specific reasons for this result (see ***Sec. 4.5.2*: Issues with the Term "Inconclusive"**).[301] For example:

- *The [serology test] was not able to provide any information regarding whether blood is or is not present due to [reason: insufficient sample/test malfunction].*
- *The [serology test] was not able to provide support for whether blood is or is not present due to [reason: insufficient sample/interfering substance/test malfunction].*

4.6.3 Reporting and Testifying to Serology Results

Clear communication of how the serology testing results do (or do not) relate to the DNA profile developed is essential. Clear communication may be accomplished, in part, by reporting the limitations in the testing method, including data from internal validation studies and other published material. It is important to clearly state in a formal report which questions analysis did and did not address.

Serological testing alone cannot help to address questions about *how* or *when* the biological material was deposited. Reporting caveats and method statements are crucial, as cases are often adjudicated without the appearance of an expert witness in court (see **Callout Box 4.2**).

[301] Organization of Scientific Area Committees (OSAC). *Standard for Use of Serological Testing Methods Associated with Forensic Investigations, Version 2.0. OSAC Proposed Standard 2021-S-0028*. 2022. https://www.nist.gov/system/files/documents/2022/10/31/OSAC%202021-S-0028%20Standard%20Use%20of%20Serological%20Testing%20Methods_REGISTRY%20VERSION.pdf. ANSI National Accreditation Board (ANAB). *AR 3125: Accreditation Requirements for Forensic Testing and Calibration (2023)*. 2023. https://anab.qualtraxcloud.com/ShowDocument.aspx?ID=12371. Requirement 7.8.1.2.

Callout Box 4.2: Example Serology Result and Limitation Statements

General limitation statements for serology tests:

While a positive test result indicates the possible presence of a biological material of interest, the test result does not constitute the identification of that material. A negative test result indicates that the material of interest was not detected; however, it is not confirmation of its absence.[302]

The serological opinions expressed do not provide information regarding the timing, mechanisms, or actions that may have led to the deposition or absence of the biological material.

Specific results and limitations:

Results statement: *At least 50 spermatozoa were observed on the microscope slide prepared from a small portion of the item. It is the opinion of this analyst that semen is present on Item X.*

Limitations: *Microscopic sperm detection is a visual inspection that relies, among other elements, on the analyst's visual acuity. The technique is prone to subjectivity and conclusions may vary between analysts.*

Results statement: *The possible presence of human blood was indicated using the [blood card test].*

Limitations: *False positives have been shown to occur with the [blood card test]. This test has been shown to cross-react with the blood of the domestic ferret and higher primate species. False positive results may also occur with saliva. Trace amounts of hemoglobin may also be present in other biological materials.*[303]

Results statement: *Item X was examined using the acid phosphatase (AP) reagent, and there was no indication for seminal fluid.*

Limitations: *Due to sampling variation and the sensitivity of the test, this information cannot confirm the absence of seminal fluid.*

Results statement: *Alpha-amylase was indicated using the [saliva card test].*

Limitations: *The detection of an elevated level of amylase indicates, but does not conclusively establish, the presence of saliva. Sources of amylase include saliva, vaginal secretions, and bacteria from non-human sources.*

Results Statement: *Blood was indicated with [test].*

Limitations: *This positive test result should not be interpreted as a definitive statement regarding the presence of human blood. Although the test is sensitive to blood, this test is not specific and can return a positive test result in the presence of other kind of materials, such as non-human blood, some cleaning agents, and some fruits and vegetables that contain plant peroxidases. Additionally, a positive result is reported when a reaction occurs at or above a minimum threshold; therefore, a negative result may result not from the complete absence of blood, but rather from blood at a level below the detection threshold.*

[302] Scientific Working Group on DNA Analysis Methods (SWGDAM). *Guidelines for the Collection and Serological Examination of Biological Evidence*. 2015. https://www.swgdam.org/_files/ugd/4344b0_b3deba7a272b4b268d7f522840607410.pdf. Standard 11.3.

[303] Streeting CA, Chaseling J, Krosch MN, Wright K. A Comparison of ABAcard® Hematrace® and RSID™-Blood Tests on Dried, Diluted Bloodstains Treated with Leucocrystal Violet or Luminol. *Australian Journal of Forensic Sciences*. 2022; 54(1):108-18. doi:10.1080/00450618.2020.1781256.

When testifying, the expert should, at a minimum, express the limitations of the method to give the factfinder proper understanding of the value of the test. In disclosing the limitations, it may be helpful to note that they do not mean that the test has no value, only that the value is constrained by the limitations described.

The analyst also should clearly communicate the relationship between serology testing and the DNA profile developed. That a sample contains biological material or cell types does not necessarily mean that the DNA profile must have been derived from that material.

4.6.4 Reporting the Numerical Value of the Serology Results Using a Bayesian Network

Another way to approach reporting serological results for investigative purposes is to assess the value of the results similarly to probabilistic DNA comparisons. This is accomplished by assigning the probability of the results given the proposition that the biological material is (or is not) of a given nature.[304] The University of Lausanne has developed a software approach for analysts to accomplish this using Bayesian networks.[305] Bayesian networks are a marriage between graph theory and probability theory.[306] A Bayes net graphically represents the relationship between variables as conditional probabilities. The user can input the results of the test, the color of the swab, where the test was made, and the quantity of DNA. **Callout Box 4.3** presents an example of how a serology result using a Bayesian network could be reported. Because the opinion is used to decide whether to proceed with DNA analysis, or for investigative purposes, it is permissible for the scientist to assign their prior odds that the fluid is (or is not) of a given nature. These odds would be subjective and based on factors such as the color and appearance of the stain and should be used for investigative purposes only (i.e., not for court). Indeed, it is not appropriate for scientists to assign prior odds about issues that are raised in court. This limitation needs to be stated in the FSSP's report.

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[304] De Wolff TR, Kal AJ, Berger CEH, Kokshoorn B. A Probabilistic Approach to Body Fluid Typing Interpretation: An Exploratory Study on Forensic Saliva Testing. *Law, Probability and Risk*. 2015; 14(4):323–39. doi:10.1093/lpr/mgv014; de Zoete J, Curran J, Sjerps M. A Probabilistic Approach for the Interpretation of RNA Profiles as Cell Type Evidence. *Forensic Science International: Genetics*. 2016; 20:30-44. doi:10.1016/j.fsigen.2015.09.007; de Zoete J, Oosterman W, Kokshoorn B, Sjerps M. Cell Type Determination and Association with the DNA Donor. *Forensic Science International: Genetics*. 2016; 25:97-111. doi:10.1016/j.fsigen.2016.08.004; Iacob D, Fürst A, Hadrys T. A Machine Learning Model to Predict the Origin of Forensically Relevant Body Fluids. *Forensic Science International: Genetics Supplement Series*. 2019; 7(1):392-4. doi:10.1016/j.fsigss.2019.10.025; Ypma RJF, Maaskant-van Wijk PA, Gill R, Sjerps M, van den Berge M. Calculating LRs for Presence of Body Fluids from mRNA Assay Data in Mixtures. *Forensic Science International: Genetics*. 2021; 52:102455. doi:10.1016/j.fsigen.2020.102455.

[305] Basset P, Blandin P, Grini A, Delemont S, Samie L, Castella V. A Simplified Protocol for the Detection of Blood, Saliva, and Semen from a Single Biological Trace Using Immunochromatographic Tests. *Forensic Science, Medicine and Pathology*. 2022; 18(2):141-8. doi:10.1007/s12024-021-00453-2; Samie L, Champod C, Delémont S, Basset P, Hicks T, Castella V. Use of Bayesian Networks for the Investigation of the Nature of Biological Material in Casework. *Forensic Science International*. 2022; 331:111174. doi:10.1016/j.forsciint.2022.111174; Ypma RJF, Maaskant-van Wijk PA, Gill R, Sjerps M, van den Berge M. Calculating LRs for Presence of Body Fluids from mRNA Assay Data in Mixtures. *Forensic Science International: Genetics*. 2021; 52:102455. doi:10.1016/j.fsigen.2020.102455.

[306] Biedermann A, Taroni F. Bayesian Networks for Evaluating Forensic DNA Profiling Evidence: A Review and Guide to Literature. *Forensic Science International: Genetics*. 2011; 6(2):147-57. doi:10.1016/j.fsigen.2011.06.009; Evett IW, Gill PD, Jackson G, Whitaker J, Champod C. Interpreting Small Quantities of DNA: The Hierarchy of Propositions and the Use of Bayesian Networks. *Journal of Forensic Sciences*. 2002; 47(3):520-30. doi:10.1520/jfs15291j.

Callout Box 4.3: Reporting Serology Results Using a Bayesian Network

If an analyst uses Bayesian networks to convey the value of the serology results or to decide whether to further analyze the item or to provide investigative information, an expression of the results with an associated caveat statement may look like this:

"The information about the nature of the biological material has been obtained by considering the probability of observations (i.e., results of indicative tests, quantification, DNA analysis) given the proposition that the specimen contains the biological material of interest and the probability of the same observations based on the alternative proposition that the specimen does not contain that biological material. The ratio of these probabilities is called a likelihood ratio (LR). The latter has been assigned using a Bayesian network (a probabilistic graphical model) that takes into account the set of observations and the probabilities of false negatives and false positives.

Regarding the nature of the biological material on Item 1, an LR of 2 was assigned. This means that it is on the order of two times more likely to make these observations if the sample contains saliva than if it does not. A prior probability of ½ was assigned to the proposition that there is saliva on the item. For this prior probability and LR, the posterior probability that the sample contains saliva is 67%, and the probability that it does not contain saliva is 33%.

The conclusions about the nature of the biological material analyzed are for investigative purposes only. It is not possible, at this time, to associate all or part of a DNA profile with a given biological material. A new interpretation will be necessary if the case information changes, if new information indicates that the prior probability used is not appropriate, or if the focus shifts to the activities alleged by the parties."

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5. Reporting

5.1 Introduction and Scope

This chapter presents human factors considerations related to the communication of DNA and other biological results. Two closely related chapters include ***Chapter 4: Quantitative and Qualitative Ways to Express DNA Results***, which focuses on the different ways to convey the meaning of results, and ***Chapter 6: Pre-Trial Preparation and Testimony***, which focuses on best practice for analysts testifying to their analyses and the content of their reports.

The terms *reporting* and *report* refer to any format of communication. *End-user* encompasses anyone who uses the report for the purpose of informing an action or decision, and can include DNA analysts, law enforcement investigators, legal professionals, defendants, complainants, or court personnel. *Factfinder* refers to those tasked with making the ultimate decision in the case—the jury or judge.

DNA methods, results, and opinions are communicated through either *formal written reports* or *informal communication* (e.g., verbal conversations, email correspondence). Through reports that are balanced, transparent, and state the caveats and limitations associated with the analysis and results, analysts can provide the end-user the best opportunity to understand what the results do and do not mean. DNA reports should contain the opinions the DNA analyst intends to deliver during testimony.

A discussion on reporting serology results is presented in ***Sec. 4.6: Interpretation and Expression of Serological Screening Results***. Reporting opinions when there is a DNA comparison result, but the end-users' interest is the actions or timing related to the deposition of the DNA is discussed in ***Chapter 7: How and When Questions in DNA Analysis***.

5.2 Human Factors Challenges When Producing and Reading a DNA Report

DNA reports are read by end-users with varying degrees of scientific, statistical, and legal understanding. Human factors challenges associated with producing a comprehensible DNA report include:

- DNA evidence is not able to directly address many of the investigative questions that are asked.[307]

[307] Evett IW. Avoiding the Transposed Conditional. *Science & Justice*. 1995; 35(2):127-31. doi:10.1016/S1355-0306(95)72645-4.

- The end-user may not have training or expertise in science, statistics, or DNA analysis.[308] There is research showing that even forensic analysts misunderstand forensic reports at times.[309]
- DNA results can be complex, and the analyst must strike a balance between making the results easy to understand and not losing information that is critical for the end-user to fully comprehend what the results do and do not mean.[310]
- When DNA reports are complex or laden with jargon, the end-user may lose interest, skip parts, or follow cognitive shortcuts that may result in missing critical information. As a result, end-users can interpret the same forensic report differently.[311]
- The end-user may have preexisting misconceptions about what DNA results can and cannot say about the issue(s) in the case.
- Reporting is not standardized; there is great variation between the reports that FSSPs produce, both between forensic science service providers (FSSPs) and within an FSSP. An end-user's knowledge and experience will also influence their interpretation. Hence, there is likely to be variation in end-user comprehension of a report.
- An analyst who writes a report cannot always be contacted to rephrase, answer additional questions, or highlight a specific aspect of analysis. A formal report needs to contain enough information to stand alone.
- DNA reports should communicate the caveats and limitations associated with the reported results to help the end-user understand what the results do and do not mean. Communicating the caveats and limitations aids in avoiding over- or under-valuation of the results, or misinterpretation of the results (see **Callout Box 5.1**).[312]

This chapter presents ways to report DNA results that can help to overcome these challenges.

[308] McQuiston-Surrett D, Saks MJ. The Testimony of Forensic Identification Science: What Expert Witnesses Say and What Factfinders Hear. *Law and Human Behavior*. 2009; 33(5):436-53. doi:10.1007/s10979-008-9169-1; van Straalen EK, de Poot CJ, Malsch M, Elffers H. The Interpretation of Forensic Conclusions by Criminal Justice Professionals: The Same Evidence Interpreted Differently. *Forensic Science International*. 2020; 313:110331. doi:10.1016/j.forsciint.2020.110331.

[309] de Keijser J, Elffers H. Understanding of Forensic Expert Reports by Judges, Defense Lawyers and Forensic Professionals. *Psychology, Crime & Law*. 2012; 18(2):191-207. doi:10.1080/10683161003736744.

[310] Ibid.; Howes LM, Kirkbride KP, Kelty SF, Julian R, Kemp N. Forensic Scientists' Conclusions: How Readable Are They for Non-Scientist Report-Users? *Forensic Science International*. 2013; 231(1-3):102-12. doi:10.1016/j.forsciint.2013.04.026; Thompson WC, Grady RH, Lai E, Stern HS. Perceived Strength of Forensic Scientists' Reporting Statements About Source Conclusions. *Law Probability & Risk*. 2018; 17(2):133-55. doi:10.1093/lpr/mgy012.

[311] van Straalen EK, de Poot CJ, Malsch M, Elffers H. The Interpretation of Forensic Conclusions by Criminal Justice Professionals: The Same Evidence Interpreted Differently. *Forensic Science International*. 2020; 313:110331. doi:10.1016/j.forsciint.2020.110331.

[312] McQuiston-Surrett D, Saks MJ. The Testimony of Forensic Identification Science: What Expert Witnesses Say and What Factfinders Hear. *Law and Human Behavior*. 2009; 33(5):436-53. doi:10.1007/s10979-008-9169-1; van Straalen EK, de Poot CJ, Malsch M, Elffers H. The Interpretation of Forensic Conclusions by Criminal Justice Professionals: The Same Evidence Interpreted Differently. *Forensic Science International*. 2020; 313:110331. doi:10.1016/j.forsciint.2020.110331.

Callout Box 5.1: DNA Evidence is Only One Piece of the Puzzle

Case Study: DNA Database Association.[313]

Rare events happen. In 1999, a six-locus DNA database search led authorities to charge Raymond Easton with a burglary that took place approximately 175 miles from where he lived. The Random Match Probability (RMP) was 1 in 37 million, but a later 10-locus comparison excluded Mr. Easton. That Easton had a strong alibi, suffered from advanced Parkinson's disease, and was not able to walk without aid for more than a few meters was initially disregarded.

This case highlights the potential for a miscarriage of justice when non-DNA evidence is not considered. The probability that an individual may have left biological material at the crime scene is based on the combined strength of the scientific or non-scientific evidence and background information.[314]

Case Study: Laboratory Contamination.[315]

Another example of using DNA evidence to arrest and charge an individual without considering the contradictory evidence is the case of Adam Scott in 2011. The only evidence against Scott was the finding of a few spermatozoa on intimate swabs collected from the sexual assault victim with a profile that *matched* Scott's. Scott claimed to be in his hometown more than 200 miles away at the time of the incident.

An analyst testified that the DNA evidence provided "strong scientific support for the view that Adam Scott had sexual intercourse with [the victim] rather than he did not." This statement was inappropriate because a short tandem repeat (STR) profile by itself cannot be used to ascertain cell source or to define the activity that occurred. Two months after Scott's arrest, mobile phone records corroborated his version of events. After five months in custody, Scott was released.

A subsequent investigation revealed that the day before processing the swabs from the sexual assault victim, the FSSP had processed a DNA swab from Scott in an unrelated case. The disposable plastic plate used to analyze Scott's sample had been reused when processing the sexual assault case.

Case Study: Incidental DNA Transfer.[316]

Lukis Anderson was arrested and detained for five months because his profile in a Combined DNA Index System (CODIS) database matched the profile found in material under the fingernails of a murder victim. Anderson stated he did not know the victim but that he had consumed an abundance of alcohol at the time. After it was learned that Anderson was in the hospital when the murder occurred, the charges were dropped.

Further investigation revealed that approximately three hours before paramedics removed the victim's body in an ambulance, they had transported Anderson in the same ambulance. The exact cause of the DNA transfer will never be known. The mechanism might have been a shared pulse oximeter, a paramedic's uniform, equipment in the ambulance, or something else. Even though Anderson did not go to trial or prison, he was wrongly incarcerated for five months due to the initial overweighting of DNA evidence when the hospital records clearly supported a strong alibi. This case, like the ones above, illustrates the danger in using DNA results in isolation.

[313] Gill P. DNA Evidence and Miscarriages of Justice. *Forensic Science International*. 2019; 294:e1-e3. doi:10.1016/j.forsciint.2018.12.003.

[314] Jackson G, Jones S, Booth G, Champod C, Evett IW. The Nature of Forensic Science Opinion - a Possible Framework to Guide Thinking and Practice in Investigations and in Court Proceedings. *Science & Justice*. 2006; 46(1):33-44. doi:10.1016/s1355-0306(06)71565-9.

[315] Gill P. How Misuse of DNA Evidence Has Led to Miscarriages of Justice. *The Justice Gap*. 2017. Accessed March 27, 2024. https://www.thejusticegap.com/misuse-dna-evidence-led-miscarriages-justice/

[316] Worth K. Framed for Murder by His Own DNA. Accessed March 27, 2024. https://www.themarshallproject.org/2018/04/19/framed-for-murder-by-his-own-dna.

5.3 Purpose of a DNA Report

The purpose of DNA reporting is to provide a clear and comprehensible account of the methods the analyst used, the results, and the analyst's interpretation of those results. Typically, the interpretations and opinions in formal reports will be reviewed by another qualified analyst (a technical reviewer) as part of the FSSP's quality assurance (QA) and quality control (QC) measures prior to an end-user receiving it (see ***Sec. 8.4.2: Technical Peer Review***).

Early in an investigation or analysis, an analyst and end-user might communicate information informally via email, phone calls, or meetings. The analyst may use these communications as an opportunity to express caveats and limitations about DNA testing. All communication about the case between the analyst(s) and investigators or attorneys should be documented in the case file.

The analyses performed will depend on the case circumstances,[317] the resources available, and whether there is a Person of Interest (POI) to compare a DNA profile to (see ***Sec. 5.3.1: Reporting When There Is a POI Profile for Comparison).*** These factors will inform the content of the report.

The factfinder is concerned with the broadest offense-level question: Has the prosecution met its burden of proof regarding the defendant's guilt? To resolve this question, end-users and factfinders may consider questions such as: What happened? Who could be involved? How many people were involved? Who could have been an innocent bystander? Is the defendant the source of the DNA? Could the defendant's DNA have been deposited by another individual, object, or surface? How many other people might share the defendant's DNA profile?

DNA evidence alone cannot answer the question of guilt, nor can DNA results answer any of these questions directly.[318] However, by reporting and testifying, DNA analysts can contribute to end-users' understanding and appropriate use of the DNA evidence (see ***Chapter 6: Pre-Trial Preparation and Testimony***). To this end, the analyst must make clear that the DNA results could mislead an investigation if used in isolation. As one Australian judge explained in response to *R. v. Jama*, a case in which switched samples led to a wrongful conviction and imprisonment for rape:[319]

> [t]he obviously unreserved acceptance of the reliability of the DNA evidence appears to have so confined thought that it enabled all involved to leap over a

[317] Cook R, Evett IW, Jackson G, Jones PJ, Lambert JA. A Model for Case Assessment and Interpretation. *Science & Justice*. 1998; 38(3):151-6. doi:10.1016/S1355-0306(98)72099-4.

[318] Ibid.; Hicks T, Buckleton J, Castella V, Evett IW, Jackson G. A Logical Framework for Forensic DNA Interpretation. *Genes (Basel)*. 2022; 13(6):957. doi:10.3390/genes13060957; Jackson G, Jones S, Booth G, Champod C, Evett IW. The Nature of Forensic Science Opinion - a Possible Framework to Guide Thinking and Practice in Investigations and in Court Proceedings. *Science & Justice*. 2006; 46(1):33-44. doi:10.1016/s1355-0306(06)71565-9.

[319] Vincent FHR. *Report: Inquiry into the Circumstances That Led to the Conviction of Mr Farah Abdulkadir Jama*. 2010. https://catalogue.nla.gov.au/catalog/4926898. p. 10.

veritable mountain of improbabilities and unexplained aspects that, objectively considered, could be seen to block the path to conviction.

5.3.1 Reporting When There Is a POI Profile for Comparison

A POI is anyone whose DNA profile is relevant, including for elimination purposes, to the case questions. A POI could be a suspect, a complainant, a deceased, an individual with legitimate access to a crime scene, or relatives of a POI. When a POI's profile is available for comparison, the analyst interprets and compares the DNA data, assigning numerical value(s) when applicable. These results are presented in a formal written, and technically reviewed, report. This report will form the basis of the analyst's testimony, and at times, may be used in place of testimony (such as in plea negotiations). It is critical that the report contains all information necessary for the end-user to understand the value and limitations of the DNA results (see ***Sec. 5.5: Human Factors Considerations in the Contents of a Report Containing Biological Results and Comparisons***).

5.3.2 Reporting in the Absence of a POI Profile for Comparison

When there is no POI profile to compare a forensic profile to, analysts still may be able to contribute to the investigation through *investigative reporting*.[320] In the absence of a POI, it is critical for the end-user to understand that while investigative results can assist in investigative decisions, they can also misdirect an investigation and may contribute to tunnel vision.[321] Several types of investigative DNA results are discussed in the sections that follow.

5.3.2.1 Unknown-to-Unknown Comparisons

Comparing unknown DNA profiles between cases can identify a common source, linking cases to the same offender. But the term *match* should be avoided, and similarities should be reported with caveats regarding the preliminary nature of the comparisons, as they are not accompanied by any statistical analysis.

There may be software tools available that can aid the analyst with these comparisons (e.g., in-house programs, database likelihood ratio [DBLR] mixture-to-mixture tools[322]); however, in the absence of such tools and established thresholds for reporting such *possible inclusions,* forming a consistent line at which to report the similarities or differences between profiles can be

[320] Hicks T, Buckleton J, Castella V, Evett IW, Jackson G. A Logical Framework for Forensic DNA Interpretation. *Genes (Basel)*. 2022; 13(6):957. doi:10.3390/genes13060957.

[321] Elaad E. Tunnel Vision and Confirmation Bias among Police Investigators and Laypeople in Hypothetical Criminal Contexts. *SAGE Open*. 2022; 12(2):1-10. doi:10.1177/:21582440221095022; Findley KA, Scott MS. The Multiple Dimensions of Tunnel Vision in Criminal Cases. *Wisconsin Law Review*. 2006:291-397.

[322] Kelly H, Kerr Z, Cheng K, Kruijver M, Bright JA. Developmental Validation of a Software Implementation of a Flexible Framework for the Assignment of Likelihood Ratios for Forensic Investigations. *Forensic Science International: Reports*. 2021; 4:100231. doi:10.1016/j.fsir.2021.100231; Schuerman C, Kalafut T, Buchanan C, Sutton J, Bright JA. Using the Nondonor Distribution to Improve Communication and Inform Decision Making for Low LRs from Minor Contributors in Mixed DNA Profiles. *Journal of Forensic Sciences*. 2020; 65(4):1072-84. doi:10.1111/1556-4029.14306.

complex depending on the nature of the DNA profiles involved. In these situations, the FSSP should have and follow clear procedures about how to determine when there is sufficient similarity to report such investigative information.

5.3.2.2 Investigative Leads Produced Following DNA Database Searches

Criminal justice DNA databases[323] are a valuable tool that can be used to generate investigative leads by suggesting *associations* between individuals and forensic samples (i.e., an unknown DNA profile developed from a sample collected at a crime scene) or between forensic samples. According to the Federal Bureau of Investigation (FBI), "[a]s of August 2023, CODIS has produced over 674,405 hits assisting in more than 656,893 investigations."[324] The vast majority of these investigative leads come before police have a specific suspect in mind. How should FSSPs report these "cold hits" to help investigators make the best use of the lead? The major human-factors issues are tunnel vision and confirmation bias. When a "hit"[325] is reported, investigators may fail to uncover, or be inclined to discount, information on other possible sources of the DNA. That would be an instance of tunnel vision.[326] Likewise, investigators could be overimpressed with other evidence pointing toward the POI raised from the database search. That would be confirmation bias.[327]

DNA database operational procedures[328] typically notify police that a new sample from the individual found in the database search should be acquired and submitted for a new comparison. However, these investigative leads can be communicated to law enforcement investigators in a variety of formats, and with varying degrees of information, formality, and review. Furthermore, some FSSPs may provide statistical analysis along with notification of an association to an individual, which may lead law enforcement investigators to believe that there is no need for the FSSP to make a new comparison between the profile from the unknown and the profile developed within the laboratory from the POI's new sample.

[323] The Combined DNA Index System (CODIS) is the DNA database primarily used in the United States. Other countries may use the CODIS software for profile searching within a specified database or they may have their own equivalent DNA database system. The FBI has established specific requirements for FSSPs participating in CODIS searches and rules governing what types of profiles may be entered into the various databases. Issues surrounding unregulated databases and profile eligibility for evidentiary profiles are beyond the scope of this report.

[324] Federal Bureau of Investigation (FBI). Law Enforcement Resources: CODIS-NDIS Statistics. Accessed March 27, 2024. https://le.fbi.gov/science-and-lab/biometrics-and-fingerprints/codis/codis-ndis-statistics.

[325] The EWG discourages use of the word "hit," as it may have the same misleading connotation as "match."

[326] Elaad E. Tunnel Vision and Confirmation Bias among Police Investigators and Laypeople in Hypothetical Criminal Contexts. *SAGE Open*. 2022; 12(2):1-10. doi:10.1177/:21582440221095022. "Tunnel vision is over-reliance on internal sources while ignoring accurate external information."

[327] Ibid. "Confirmation bias is over-reliance on external sources that are not necessarily accurate."

[328] Although many states formulate their own operational procedures, much if not all of the content is shaped by the *NDIS Operational Procedures*. Federal Bureau of Investigation (FBI). *Law Enforcement Resources: National DNA Index System (NDIS) Operational Procedures Manual, Version 12*. 2022. https://le.fbi.gov/file-repository/ndis-operational-procedures-manual-version-12-070123.pdf/view.

Prior to communicating an association, an FSSP should perform an internal quality process such as an administrative check. These processes vary depending on the category of association (e.g., an association between two forensic samples) as well as the jurisdiction. This quality process is not designed to replace the need for the formal comparison and statistical analysis that occurs with the submission of a POI reference sample.

To mitigate these risks when notifying investigators of an association in the database, FSSPs must communicate the limitations of the investigative lead.[329] In particular, they should clearly state that the lead could be wrong for several reasons, including shared genetic characteristics because of relatives or by chance, or sample and data handling errors.[330] Additionally, erroneous associations can occur through contamination, both before the sample reaches the laboratory, or during laboratory processing.[331]

No standards or guidance documents in the United States explicitly require such limitation reporting.[332] Regardless of whether the association to a POI results from a database search or from a comparison to a preexisting POI, guidance documents have highlighted the need for law enforcement investigators to be cautious when DNA evidence is the sole evidence in the case.[333] The sole use of any forensic evidence can be problematic (see **Callout Box 5.1**).

Recommendation 5.1: To help reduce the risk of tunnel vision and confirmation bias in an investigation, forensic science service providers should report the limitations of DNA database searches to law enforcement investigators, including that associations can occur with individuals who are not the source of the DNA.

5.3.2.3 Distinguishing Between Male and Female DNA

FSSPs may use data developed during analysis to indicate in a report if female or male DNA is present and may even provide an assignment of the minimum number of male donors in a sample. This biological sex information has the potential to assist an investigation by focusing the testing

[329] Gill P. DNA Evidence and Miscarriages of Justice. *Forensic Science International*. 2019; 294:e1-e3. doi:10.1016/j.forsciint.2018.12.003.

[330] Morrison A. New York City Agency Has Underreported Lab Errors in DNA Database It Oversees. The Appeal. Feb 24, 2020. Accessed March 27, 2024. https://theappeal.org/new-york-city-dna-database-lab-errors/

[331] Elster N. How Forensic DNA Evidence Can Lead to Wrongful Convictions. *JSTOR Daily*. 2017. Accessed March 27, 2024. https://daily.jstor.org/forensic-dna-evidence-can-lead-wrongful-convictions/; Worth K. Framed for Murder by His Own DNA. Accessed March 27, 2024. https://www.themarshallproject.org/2018/04/19/framed-for-murder-by-his-own-dna.

[332] The FBI does provide a factsheet about the general process following a database lead. Federal Bureau of Investigation (FBI). Frequently Asked Questions on CODIS and NDIS. Accessed March 27, 2024. https://www.fbi.gov/how-we-can-help-you/dna-fingerprint-act-of-2005-expungement-policy/codis-and-ndis-fact-sheet.

[333] Gill P, Hicks T, Butler JM, Connolly E, Gusmao L, Kokshoorn B, Morling N, van Oorschot RAH, Parson W, Prinz M, Schneider PM, Sijen T, Taylor D. DNA Commission of the International Society for Forensic Genetics: Assessing the Value of Forensic Biological Evidence - Guidelines Highlighting the Importance of Propositions: Part I: Evaluation of DNA Profiling Comparisons Given (Sub-) Source Propositions. *Forensic Science International: Genetics*. 2018; 36:189-202. doi:10.1016/j.fsigen.2018.07.003.

(and investigation) on specific items, corroborating a victim or witness account of the unknown offender (or numbers of offenders), or redirecting an investigation if the biological sex detected on a critical item (e.g., weapon) runs counter to the original investigative theory.

There are several ways that end-users can overvalue and subsequently misinterpret these results. For example:

- Reporting the presence of an unknown female individual could lead to the elimination of all potential male POIs.
- Male DNA detection could lead to an inference about the nature of the body fluid or possible activities if the end-user interprets male DNA to mean semen.
- An investigation could stall because the biological sex or assigned number of contributors (NOC) runs counter to the investigative theory.

Although biological sex information can be helpful in an investigation, it is important for an end-user to be aware that such information is at the DNA level and (1) may not reflect how an individual identifies or appears to others, or (2) the donor may have genetic deletions or mutations that impact the detection of data at the sex-indicating markers. As a result, biological sex information should be interpreted with caution and when reporting the results, analysts should alert the end-user to these limitations (see ***Appendix 5.1***).

5.3.2.4 Possible Explanations for DNA Results

Explanations are generated after the results have been obtained and are communicated as a justification for why the results were observed.[334] A submitting party may ask about these possibilities to guide their investigation or pursue other items for testing. Explanations are generally informal, one-sided considerations that should only be expressed in the very early stages of an investigation. Furthermore, it is not feasible to provide an exhaustive list of all potential explanations for the observed results. The European Network of Forensic Science Institutes (ENFSI) states:[335]

> In the context of a forensic science evaluation, an explanation has been recognized as an intermediate consideration for use when exploring less formal alternatives. A key characteristic of explanations is that they are generated after the forensic findings have been obtained. While an explanation has the potential to account for particular observations, it does not qualify as a formal proposition because – often – it may be a statement of the obvious, speculative or fanciful.

[334] Evett IW, Jackson G, Lambert JA. More on the Hierarchy of Propositions: Exploring the Distinction between Explanations and Propositions. *Science & Justice*. 2000; 40(1):3-10. doi:10.1016/S1355-0306(00)71926-5; Hicks T, Buckleton J, Castella V, Evett IW, Jackson G. A Logical Framework for Forensic DNA Interpretation. *Genes (Basel)*. 2022; 13(6):957. doi:10.3390/genes13060957.

[335] European Network of Forensic Science Institutes (ENFSI). *ENFSI Guideline for Evaluative Reporting in Forensic Science: Strengthening the Evaluation of Forensic Results across Europe (STEOFRAE), Version 3.0*. 2015. https://enfsi.eu/wp-content/uploads/2016/09/m1_guideline.pdf.

Since explanations are one-sided and cannot encompass all possibilities, they must be accompanied with a caveat emphasizing that they can be misleading because there is limited or no scope to test them in a way that appropriately evaluates the evidence given the case circumstances.

In this way, explanations are not the same as formal propositions considered when interpreting results given questions that consider alleged activities (see ***Chapter 7: How and When Questions in DNA Analysis***). **Table 5.1**, adapted from Hicks et al.,[336] contains examples of possible explanations for a DNA result that attempts to list all realistic possibilities to avoid bias.

Table 5.1: An example of possible explanations for DNA results when there is no POI.[337]

Results	Possible Explanations
No DNA profile foreign to the victim was detected from the vaginal swab in a sexual assault kit (SAK).	• There was no ejaculation. • A condom was used. • No intercourse occurred. • The time since deposition has been too long. • There was intercourse but semen was lost following showering or cleaning. • There was intercourse but the donor has a low sperm count. • The swab taken did not recover the semen due to poor procedures.

Table adapted from Hicks et al., 2022.[338]

Some jurisdictions outside of the United States[339] will state possible explanations in a formal written report. A formal written report with a list of possible explanations for the DNA results (with appropriate scientific literature referenced) is a transparent way to communicate to the end-user that there could be many explanations for a result. However, it is not possible to present all explanations, nor to provide guidance on the probability of any explanation.

In the United States, current practice typically involves giving explanations via verbal or email communication. While this may be acceptable in the early phases of the case, explanations are generally of limited assistance and can be potentially misleading when relayed to factfinders in court.

If used inappropriately, explanations could mislead an investigation. Therefore, if an FSSP communicates explanations for DNA results during the early phases of a case, these explanations must be accompanied with a statement to inform the end-user of the caveats and limitations

[336] Hicks T, Buckleton J, Castella V, Evett IW, Jackson G. A Logical Framework for Forensic DNA Interpretation. *Genes (Basel)*. 2022; 13(6):957. doi:10.3390/genes13060957.

[337] Ibid.

[338] Ibid.

[339] In the experience of members of this EWG, this occurs in some European countries.

(see ***Appendix 5.1***). Giving an explanation amounts to *speculating* on what happened (see ***Chapter 7: How and When Questions in DNA Analysis***).

5.4 Report Formats

The purpose of a DNA report is to provide the end-user with a clear and comprehensible account of the methods used, the results, and the analyst's interpretations or opinions. The content and format may vary based on the purpose of the examination and the status of the case, but the DNA results and opinions should always be communicated in a logical, balanced, transparent, and robust way.[340]

5.4.1 Narrative, Tabular, Lists, and Combined Report Formats

When formatting a DNA report, FSSPs should balance brevity and simplicity while providing enough information for the end-user to understand the DNA results. Report format can vary and may use one technique or a combination of techniques, including narratives, tables, and lists. **Callout Box 5.2** presents an example of how the same DNA *result* can be presented in different ways. Similarly, **Callout Box 5.3** presents an example of how the same DNA *comparison* can be presented in different ways.

Callout Box 5.2. Example Formats to Present a DNA Result

In the examples that follow, the same information is presented in different formats: narrative, tabular, and list. This type of result would be presented in the "Profile Results, Suitability Assessment, and Number of Contributor Assignments" section of the report (see ***Sec. 5.5.4: Profile Results, Suitability Assessment, and Number of Contributor Assignments***).

Narrative

"The DNA profile obtained from Item 1 (swab of door handle) has been assigned as three contributors and is suitable for comparison to reference samples. The DNA profile has been entered into CODIS."

Tabular

Item	Item description	DNA profile obtained?	Number of contributors assigned	Suitable for comparisons?	CODIS entry?
1	Swab of door handle	Yes	3	Yes	Yes

List

Item 1: Swab of door handle

Assigned contributors: 3

Suitable for comparison: Yes

[340] European Network of Forensic Science Institutes (ENFSI). *ENFSI Guideline for Evaluative Reporting in Forensic Science: Strengthening the Evaluation of Forensic Results across Europe (STEOFRAE), Version 3.0*. 2015. https://enfsi.eu/wp-content/uploads/2016/09/m1_guideline.pdf; Jackson G. The Scientist and the Scales of Justice. *Science & Justice*. 2000; 40(2):81-5. doi:10.1016/S1355-0306(00)71947-2; Willis S. Standards for the Formulation of Evaluative Forensic Science Expert Opinion Association of Forensic Science Providers. *Science & Justice*. 2010; 50(1):49. doi:10.1016/j.scijus.2009.11.004.

Profiles entered into CODIS for searching: Yes

Callout Box 5.3: Example Formats to Present a DNA Comparison

In the examples that follow, the same information is presented in different formats: narrative, tabular, and list. This type of result would be presented in the "Propositions, DNA Comparison Statements, and Statistical Analyses" section of the report (see ***Sec. 5.5.5*: Propositions, DNA Comparison Statements, and Statistical Analyses**).

Narrative

The DNA profile from Item 1 (swab of door handle) was interpreted as originating from 3 contributors. The following 2 propositions were considered to evaluate the probability of the DNA profile:

1. *John Smith and two unknown individuals are the source of the DNA.*

OR

2. *Three unknown individuals are the source of the DNA.*

The results are of the order of 1 billion times more probable if John Smith and two unknown individuals are the source of the DNA mixture than if three unknown individuals are.

Assigned likelihood ratios (LRs) that exceed the reporting cap of 1 billion are reported as "of the order of 1 billion."

Tabular

Item	Item Description	Propositions Considered	Evaluation of Results (LR)
1	Swab of door handle	**Proposition 1:** John Smith and 2 unknown individuals are the source of the DNA mixture.	The results are of the order of 1 billion* times more probable if John Smith and 2 unknown individuals are the source of the DNA mixture than if three unknown individuals are.
		Proposition 2: 3 unknown individuals are the source of the DNA mixture.	

** Assigned LRs that exceed the reporting cap of 1 billion are reported as "of the order of 1 billion."*

List

Item 1: Swab of door handle

Assigned contributors: 3

Suitable for comparison: Yes

Proposition 1: John Smith and 2 unknown individuals are the source of the DNA mixture.

Proposition 2: 3 unknown individuals are the source of the DNA mixture.

Likelihood ratio: The results are of the order of 1 billion* times more probable if John Smith and 2 unknown individuals are the source of the DNA mixture than if 3 unknown individuals are.

* Assigned LRs that exceed the reporting cap of 1 billion are reported as "of the order of 1 billion."

Narrative reports include written explanations or paragraphs that describe the evidence or items tested, as well as the DNA results and the analyst's opinions. Tabular and list formats are generally easier for end-users to digest than narrative, particularly if there are many items to

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report, but they may be oversimplified and void of enough detail to fairly represent the caveats and limitations of the results. Narrative reports can be more detailed than tabular reports, but if they are too lengthy or technical, the end-user may miss important information. When a report includes mixed formats, it allows for more detailed explanations of tests and results, while also keeping the report organized and allowing some aspects of the results to be digested quickly by providing tabular features.

Regardless of report format, FSSPs must include the necessary caveats and limitations and be mindful of the trade-offs of presenting over-simplified results or visual shortcuts that are subjective in nature and could be misleading.[341] For example, color-coding results can create bias, where green may be seen as positive and red as negative. This could lead to overvaluing the results and misinterpretation.

5.5 Human Factors Considerations in the Contents of a Report Containing Biological Results and Comparisons

Current standards[342] and guidance documents[343] provide analysts with a framework for the minimum requirements of a DNA report but do not necessarily explore the nuances associated with qualitative and quantitative reporting of DNA results.

Presented here are the essential components to include in a report that contains DNA results and comparisons. To help end-users to understand, weigh, and use the DNA results appropriately, reports should be clearly written, comprehensive, logically structured, and transparent.[344] It is also advisable that FSSPs format and structure their reports consistently across forensic disciplines. This, in theory, should allow for the report to stand on its own and for end-users to understand the content presented in the report without the help of the analyst.

[341] McInerny GJ, Chen M, Freeman R, Gavaghan D, Meyer M, Rowland F, Spiegelhalter DJ, Stefaner M, Tessarolo G, Hortal J. Information Visualisation for Science and Policy: Engaging Users and Avoiding Bias. *Trends in Ecology & Evolution*. 2014; 29(3):148-57. doi:10.1016/j.tree.2014.01.003.

[342] ANSI National Accreditation Board (ANAB). *AR 3125: Accreditation Requirements for Forensic Testing and Calibration (2023)*. 2023. https://anab.qualtraxcloud.com/ShowDocument.aspx?ID=12371; Federal Bureau of Investigation (FBI). *Quality Assurance Standards for Forensic DNA Testing Laboratories*. 2020. https://le.fbi.gov/file-repository/forensic-qas-070120.pdf/view; International Organization for Standardization (ISO). *General Requirements for the Competence of Testing and Calibration Laboratories, ISO/IEC 17025:2017*. 2017. https://www.iso.org/standard/66912.html.

[343] European Network of Forensic Science Institutes (ENFSI). *ENFSI Guideline for Evaluative Reporting in Forensic Science: Strengthening the Evaluation of Forensic Results across Europe (STEOFRAE), Version 3.0*. 2015. https://enfsi.eu/wp-content/uploads/2016/09/m1_guideline.pdf; Scientific Working Group on DNA Analysis Methods (SWGDAM). *Recommendations of the SWGDAM Ad Hoc Working Group on Genotyping Results Reported as Likelihood Ratios*. 2018. https://www.swgdam.org/_files/ugd/4344b0_dd5221694d1448588dcd0937738c9e46.pdf; Scientific Working Group on DNA Analysis Methods (SWGDAM). SWGDAM Documents. Accessed March 27, 2024. https://www.swgdam.org/publications.

[344] Found B, Edmond G. Reporting on the Comparison and Interpretation of Pattern Evidence: Recommendations for Forensic Specialists. *Australian Journal of Forensic Sciences*. 2012; 44(2):193-6. doi:10.1080/00450618.2011.644260; Howes LM, Kirkbride KP, Kelty SF, Julian R, Kemp N. Forensic Scientists' Conclusions: How Readable Are They for Non-Scientist Report-Users? *Forensic Science International*. 2013; 231(1-3):102-12. doi:10.1016/j.forsciint.2013.04.026.

Improving comprehension of forensic evidence can be facilitated by decreasing cognitive load[345] and increasing cognitive fluency.[346] Cognitive load describes the mental effort needed to complete a particular task. Minimizing the amount of complex information an end-user needs to understand and hold in their memory allows the end-user to better absorb the most relevant information in a report.[347] Cognitive fluency is related to cognitive load but pertains to the feelings the end-user has when they are processing information in a report. The content is considered 'fluent' when the end-user finds it easy to process the information.[348]

To this end, the report must strike a balance between (1) including enough technical detail that another analyst could understand exactly what the reporting analyst has done and (2) being as clear, concise, and jargon-free as possible. Achieving this balance will aid the end-user to understand what the results do and do not mean.

Tables and figures permit end-users to compare data and information quickly and are an efficient way to present complex information. Similarly, visual information (e.g., photographs of items) can be more effective and efficient than narrative descriptions.[349]

The following sections describe the minimum contents suggested for a report containing DNA comparison results. The contents should be included in consultation with, and in addition to, the FSSP's quality management system (QMS) and accreditation standards.

- 5.5.1. Summary
- 5.5.2. Purpose of the Analysis, Case Information, and Contextual Information Management Procedures
- 5.5.3. Methodology, Technology, and Modeling/Statistical Assumptions
- 5.5.4. Profile Results, Suitability Assessment, and Number of Contributor Assignments

[345] Alter AL, Oppenheimer DM. Uniting the Tribes of Fluency to Form a Metacognitive Nation. *Personality and Social Psychology Review*. 2009; 13(3):219-35. doi:10.1177/1088868309341564; Reber R, Greifeneder R. Processing Fluency in Education: How Metacognitive Feelings Shape Learning, Belief Formation, and Affect. *Educational Psychologist*. 2016; 52(2):84-103. doi:10.1080/00461520.2016.1258173.

[346] Bull R, Blandón-Gitlin I. *The Routledge International Handbook of Legal and Investigative Psychology*. Routledge: London, UK, 2019. doi:10.4324/9780429326530; Feigenson N, Eryn N, Jalbert M. Cognitive Fluency in the Courtroom. *The Routledge International Handbook of Legal and Investigative Psychology*. 2019:102-15. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3752317

[347] Edmond G, Towler A, Growns B, Ribeiro G, Found B, White D, Ballantyne KN, Searston RA, Thompson MB, Tangen JM, Kemp RI, Martire K. Thinking Forensics: Cognitive Science for Forensic Practitioners. *Science & Justice*. 2017; 57(2):144-154. doi:10.1016/j.scijus.2016.11.005; Spellman BA, Eldridge H, Bieber P. Challenges to Reasoning in Forensic Science Decisions. *Forensic Science International: Synergy*. 2022; 4:100200. doi:10.1016/j.fsisyn.2021.100200.

[348] Alter AL, Oppenheimer DM. Uniting the Tribes of Fluency to Form a Metacognitive Nation. *Personality and Social Psychology Review*. 2009; 13(3):219-35. doi:10.1177/1088868309341564.

[349] Eldridge H. Juror Comprehension of Forensic Expert Testimony: A Literature Review and Gap Analysis. *Forensic Science International: Synergy*. 2019; 1:24-34. doi:10.1016/j.fsisyn.2019.03.001; Errickson D, Fawcett H, Thompson TJU, Campbell A. The Effect of Different Imaging Techniques for the Visualisation of Evidence in Court on Jury Comprehension. *International Journal of Legal Medicine*. 2020; 134(4):1451-5. doi:10.1007/s00414-019-02221-y; Hewson L, Goodman-Delahunty J. Using Multimedia to Support Jury Understanding of DNA Profiling Evidence. *Australian Journal of Forensic Sciences*. 2008; 40(1):55-64. doi:10.1080/00450610802050782; Ribeiro G, Likwornik H, Chin J. Visual Decision Aids: Improving Laypeople's Understanding of Forensic Science Evidence. *Journal of Applied Research in Memory and Cognition*. 2023; 12(2):230-40. doi:doi/10.1037/mac0000026.

- 5.5.5. Propositions, DNA Comparison Statements, and Statistical Analyses
- 5.5.6. Additional Information to Consider Including in a DNA Report
- 5.5.7. Caveats, Limitations, and Error
- 5.5.8. Glossary/Appendix of Technical Terms Used in the Report

FSSPs may combine sections or vary the order of the information presented. Due to the importance of reporting caveats and limitations, example language for general and specific use scenarios can be found in ***Appendix 5.1***. Reporting caveats and limitations should be considered a requirement of formally reporting or informally communicating biological results. The contents apply to DNA results both with and without a POI for comparison.

Checklists or templates could be helpful ways for FSSPs to ensure that appropriate content is included in each report. Report templates can enable harmonization within an FSSP across forensic disciplines in both report structure and use of accepted terminology. Some Laboratory Information Management Systems (LIMS) enable reports to be generated without much user interaction, but these templates are only as effective as their initial design.

If using templates, FSSPs should regularly evaluate them to ensure they (1) are evolving with changes in technology or SOPs and (2) can be understood by end-users. Having an audit template for reports may also prove useful; examples of such templates can be found in the *ENFSI Guideline for Evaluative Reporting*.[350]

5.5.1 Summary

When reports are complex or consist of long narratives, a summary presented at or towards the beginning of the report can be a helpful way to signpost certain pieces of information or results, so the end-user does not need to search. Although a summary could include the most relevant information, an analyst may not (or should not) know what the end-user will find most relevant or important.

Not all reports are of the required length to necessitate a summary. An FSSP may not have a system (e.g., LIMS) amenable to inserting a summary into their report. Furthermore, the FSSP may consider the trade-off of potentially signposting information that is not useful for the end-user an unnecessary undertaking. Therefore, the use of a summary may not be feasible or appropriate depending on the FSSP, their systems, and reporting structure.

[350] European Network of Forensic Science Institutes (ENFSI). *ENFSI Guideline for Evaluative Reporting in Forensic Science: Strengthening the Evaluation of Forensic Results across Europe (STEOFRAE), Version 3.0*. 2015. https://enfsi.eu/wp-content/uploads/2016/09/m1_guideline.pdf.

5.5.2 *Purpose of the Analysis, Case Information, and Contextual Information Management Procedures*

This section of the report should provide the end-user with a clear understanding of the following:

- The number of items analyzed
- Why each item was analyzed
- Any key issues that either the analyst or submitting party has proposed
- Any contextual information management (CIM) procedures implemented

Some of this information may be provided by the submitting party at the time of their request to the FSSP (see ***Sec. 3.2.1.1*: *The Importance of Case Assessment and Information***). It may not be feasible to include detailed information about when and where an item was collected depending on the management structure and processes used for assessment; however, if this information is key to why the analysis was performed, the report should provide that information.

FSSPs and analysts should disclose all case information and communications that influenced the examination strategy, propositions considered, and value provided to the findings.[351] This section should alert the end-user to the critical point that if any of the information that the analyst has relied on for their interpretation is found to change or be inaccurate, the analyst should be permitted to conduct a new evaluation (see ***Appendix 5.1***). The report should also state any CIM procedures the FSSP used to mitigate the potential for cognitive bias (see ***Sec. 3.3.4*: *Contextual Information Management***).

5.5.3 *Methodology, Technology, and Modeling/Statistical Assumptions*

In addition to established accreditation criteria for reporting, the FBI QAS requires that the loci, sequence region, amplification system, and the technology used (e.g., STR, Y-chromosome short tandem repeat [Y-STR] analysis) be included in the report.[352] In line with recommendations made by the International Society of Forensic Genetics (ISFG),[353] there are additional disclosures that the Expert Working Group (EWG) recommends FSSPs consider reporting: if software (e.g., probabilistic genotyping software [PGS]) methods were used to determine profile/component suitability or perform statistical analysis, FSSPs should also report the software version.[354]

[351] Forensic Science Regulator. *Codes of Practice and Conduct: Development of Evaluative Opinions. FSR-C-118, Issue 1*. 2021. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/960051/FSR-C-118_Interpretation_Appendix_Issue_1__002_.pdf.

[352] Federal Bureau of Investigation (FBI). *Quality Assurance Standards for Forensic DNA Testing Laboratories*. 2020. https://le.fbi.gov/file-repository/forensic-qas-070120.pdf/view.

[353] Gill P, Hicks T, Butler JM, Connolly E, Gusmao L, Kokshoorn B, Morling N, van Oorschot RAH, Parson W, Prinz M, Schneider PM, Sijen T, Taylor D. DNA Commission of the International Society for Forensic Genetics: Assessing the Value of Forensic Biological Evidence - Guidelines Highlighting the Importance of Propositions: Part I: Evaluation of DNA Profiling Comparisons Given (Sub-) Source Propositions. *Forensic Science International: Genetics*. 2018; 36:189-202. doi:10.1016/j.fsigen.2018.07.003.

[354] Ibid.

Reports should also include if a value was used to account for population substructure and if so, which one, the population(s) used, and whether relatives were considered.[355]

5.5.4 Profile Results, Suitability Assessment, and Number of Contributor Assignments

FSSPs should report the results of any item that was extracted for DNA. In the interest of transparency and disclosure in the report, FSSPs should consider reporting the reasons for the decisions about the item; for example, why it was not amplified or why it was determined unsuitable for comparisons.

An analyst should clearly document if and why a profile is deemed unsuitable for comparison. Generally, DNA profiles are deemed unsuitable for comparisons due to a lack of information or overly complex information; however, providing specific reasoning may help the end-user understand the decision (see ***Sec. 3.4.2*: *Suitability Considerations***).[356]

The reasoning behind some of these assignments or decisions may be too nuanced to provide in the report. However, the report should at least contain a description of the method or software tool that was used to assign the NOC and assess the profile's suitability for comparison. Example reporting caveats for the assignment of NOC and suitability determinations are presented in ***Appendix 5.1*.**

5.5.4.1 Reporting the Outcome of Differential Extractions, Cell Types, and DNA Components

Differential extraction methods attempt to separate *non-sperm* cell DNA from *sperm* cell DNA to create two fractions – or one *sperm* cell fraction using a modified method. In doing this, the goal is to simplify the DNA interpretation by minimizing the potential for a DNA mixture; however, this separation is rarely perfect, nor does it guarantee the cell types contained in either fraction.

These fractions are commonly described in reports as *non-sperm fraction* and *sperm fraction*. Describing the fractions in this manner may unintentionally mislead the end-user to believe that the *sperm fraction* must be from seminal fluid, and thus, *how* the DNA was deposited. However, this extraction type and its subsequent DNA results cannot be used to infer the presence or absence of sperm. To avoid potentially misleading end-users, FSSPs should consider:

- General fraction descriptors such as *F1* and *F2* (instead of sperm and non-sperm)
- Other neutral language as determined by the FSSP

[355] Ibid.

[356] American Academy of Forensic Sciences Standards Board. *ASB Standard 139, First Edition 2022: Reporting DNA Conclusions*. 2022. https://www.aafs.org/sites/default/files/media/documents/139_Std_Ballot02.pdf.

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- Report only the "probative fraction" for the item as noted by the FBI Quality Assurance Standards (FBI QAS) which could negate the need for any fraction descriptor[357]
- Reporting caveats that state that the sample fractions cannot be used to infer the presence or absence of sperm (see ***Appendix 5.1***)

A similar issue presents itself regarding the limitations of mixtures proportions. DNA mixture interpretation attempts to separate the genotypes of the different contributors to the mixture. FSSPs may have SOPs for describing a portion of the profile as a *major contributor* or *minor contributor* based upon manual or probabilistic interpretations. Other examples of profile descriptors are *contributor/component 1* or refer to the *percent contribution* of a contributor (e.g., 55% contribution). However, these terms may lead the end-user to infer information about how or when the DNA was deposited (e.g., the incorrect belief that if an individual aligns with the major profile, they must have directly handled the object or were the last individual to touch the object).

Therefore, the EWG does not recommend the use of *major contributor*, *minor contributor*, *contributor/component 1*, or percent contributions to describe DNA results. Instead, FSSPs should consider whether a term is needed at all to effectively communicate the DNA results. If a term is needed, reporting caveats should make it clear that these descriptors do not imply anything about how or when the DNA was deposited.

Recommendation 5.2: To reduce the potential for being misunderstood, DNA reports should contain clear, concise, and unbiased language. Terms such as major contributor and sperm fraction may be misinterpreted as indicating the nature of the biological material and how or by whom the DNA was deposited. If the report contains any such terms, it should include the limitations of those terms.

5.5.5 Propositions, DNA Comparison Statements, and Statistical Analyses

During the comparison process in a laboratory setting, the analyst may perform a two-step approach that consists of (1) assessing the similarity and differences between the forensic profile and POI profile and (2) performing a statistical analysis. The choice of interpretation and statistical analysis methods will dictate how the comparison is reported.

RMP/Combined Probability of Inclusion (CPI) methods need to use a qualitative term for the DNA comparison because they calculate a single probability for the crime sample result, based on only one proposition. If the proposition is that the POI is the source of the DNA, there is an inherent

[357] Federal Bureau of Investigation (FBI). *Quality Assurance Standards for Forensic DNA Testing Laboratories*. 2020. https://le.fbi.gov/file-repository/forensic-qas-070120.pdf/view.

assumption that the probability of the DNA results given this proposition is 1, therefore the comparison results are expressed qualitatively by stating that the profile features of a POI are either included or excluded in those present in the crime sample.

The potential problems with the RMP/CPI approach due to the lack of balance, the use of categorical language like *included*, and the potentially erroneous assumption regarding the probability of the DNA results if the POI is the contributor is 1, are discussed in ***Sec. 4.4*: Other Quantitative Expressions of DNA Results**.

LR methods calculate a *ratio* of two probabilities given a pair of mutually exclusive propositions. Unless the probability of the DNA results given each proposition is the same, then the ratio expresses the extent of support that the DNA results provide for one proposition over the other. Therefore, the results can be expressed quantitatively without the need for qualitative comparison language.

5.5.5.1 Reporting LRs

The analyst must explicitly state which competing propositions they considered in their evaluation of the DNA results. Although notations (e.g., H_1, H_2) are useful in formulae, it is not necessary for the analyst to use this or other naming conventions (e.g., defense and prosecution propositions) in the main body of the report. Typically, analysts will consider that the alternative source of the DNA is an unknown, unrelated individual. If there is case information indicating that the DNA could be from a relative, then the analyst must consider and state this within the propositions.

5.5.5.2 Reporting Other Statistical Analyses

When reporting DNA results that were not calculated under the LR framework,[358] it is important to recognize the risk that end-users may misunderstand the terms used to express the DNA comparison results. Terms such as *match*, *cannot be excluded*, and *included* can lead to erroneous inferences about the source of the DNA or the certainty of the opinion. Therefore, if using qualitative terms, the analyst must also provide the accompanying statistic that reports the value of the comparison in a clear and transparent way alongside the caveats and limitations of the terminology (see ***Appendix 5.1***).

5.5.6 Additional Information to Consider Including in a DNA Report

Due to the variability between FSSPs' policies and practices, the EWG did not include the following information as essential requirements in DNA reports. However, if these circumstances

[358] Except for visual exclusions.

occur, for transparency purposes, the FSSP should consider acknowledging the following circumstances specifically in a report:

- Propositions that consider different numbers or ranges of contributors or items that were interpreted with more than one NOC assignment
- If there was a consultation with the Technical Leader (TL) or a resolution of conflict between the analyst and technical reviewer that needed to be resolved by a third party and the reasons for these challenges
- Any quality incidents that were determined to have impacted the results of the analysis
- FSSPs that provide the profile genotypes in reports should provide the following caveat: "*The end-user should not attempt to perform DNA interpretation based upon the provided allelic designations of the evidence and Person of Interest profiles. DNA interpretation is complex and requires additional data beyond the allele designations provided."*

5.5.7 Caveats, Limitations, and Error

Perhaps one of the most important improvements that can be made to current DNA reports is for analysts to provide clear statements regarding the limitations of the DNA results and comparisons. These caveats and limitations could be provided within relevant sections of the report, as an appendix, or online via hyperlink. They should communicate to the end-user, in a transparent manner, what the statements contained within the report do and do not mean.

Caveats should also alert the end-user to one of the most common misunderstandings of DNA evidence: the findings cannot be interpreted as a direct opinion regarding who the source of the DNA is. These as well as additional caveats regarding the limitations of DNA results, adapted from Hicks et al.[359] are presented in ***Appendix 5.1*.**

Within this section, the DNA analyst should also explicitly state any assumptions they have made that could impact the results if the assumption is questioned (e.g., that there was no contamination in the sample, or that samples were labeled correctly). This section could also include any information pertaining to error or error rates, if known for a given test.[360]

[359] Hicks T, Buckleton J, Castella V, Evett IW, Jackson G. A Logical Framework for Forensic DNA Interpretation. *Genes (Basel)*. 2022; 13(6):957. doi:10.3390/genes13060957.

[360] Expert Working Group for Human Factors in Handwriting Examination. Forensic Handwriting Examination and Human Factors: Improving the Practice through a Systems Approach. NIST IR 8282r1. National Institute of Standards and Technology; 2021. doi:10.6028/NIST.IR.8282r1 ; Kloosterman A, Sjerps M, Quak A. Error Rates in Forensic DNA Analysis: Definition, Numbers, Impact and Communication. *Forensic Science International: Genetics*. 2014; 12:77-85. doi:10.1016/j.fsigen.2014.04.014; Koehler JJ. Intuitive Error Rate Estimates for the Forensic Sciences. *Jurimetrics: The Journal of Law, Science, and Technology*. 2017; 57(2):153-68. ; Murrie DC, Gardner BO, Kelley S, Dror IE. Perceptions and Estimates of Error Rates in Forensic Science: A Survey of Forensic Analysts. *Forensic Science International*. 2019; 302:109887. doi:10.1016/j.forsciint.2019.109887.

Recommendation 5.3: Forensic science service providers should include caveats and limitations in reports containing an evaluation of results considering the source of the DNA. These should make clear that:

- **If any conditioning information used in the calculation changes, a new evaluation is needed.**
- **The evaluation of the DNA comparison cannot conclusively identify an individual as the source of the DNA.**
- **The report does not provide any information about how or when the DNA was deposited.**

5.5.8 Glossary/Appendix of Technical Terms Used in the Report

In an attached or referenced online glossary, all terminology that an end-user would not readily understand should be defined in plain language.

Because it is very difficult to understand and explain the transposed conditional without notation, the FSSP could include an example in the appendix of the report. Providing it in written form can be useful to both the DNA analyst and the end-user.

5.6 The Importance of Training End-Users

This chapter has discussed some potential reporting approaches regarding format and structure to address the complexity and cognitive load associated with forensic reports. Regardless of the chosen approach, these reporting strategies will not negate the need for FSSPs to provide training to their end-users.

Training should be given not only when there are major shifts in technology or reporting formats/structure but also with the introduction of new leadership. It may also be useful to gather input and feedback from the end-users regarding different reporting formats to ensure that they are understanding the contents of the report as they are intended, or that the information they are looking for is easily accessible. These training sessions are also an opportunity to continue to reiterate the limitations associated with the DNA results and that the results should be considered within the context of all the relevant case information (see ***Sec. 9.7: Criminal Justice Partner Education***).

Recommendation 5.4: Forensic science service providers should offer training to criminal justice partners on the caveats and limitations of DNA testing so that results are properly incorporated along with other information in the case.

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5.7 Informal Communications After the DNA Report Is Released

Once the official report has been reviewed and released, the analyst may need to communicate with the end-user (including both prosecution and defense counsel) about how the DNA results should be understood. Regardless of whether the FSSP has engaged in training the end-users of their reports, due to turnover and the potential complexity of the information in a DNA report, the DNA analyst should expect and encourage end-user questions.

Informal communications (e.g., email correspondence, phone calls) between the reporting analyst and the end-user are just as crucial as the written report as they could lead the end-user to make decisions about the case (e.g., whether to charge a POI). It is important that the content of informal communications is consistent with what is in the formal report.

Because informal discussion may center around what the report does and does not mean, it remains crucial for the analyst to avoid **transposing the conditional** or relying too heavily on qualitative language during these communications (see ***Sec. 6.12: Staying in Your Lane: Avoiding Common Testimony Pitfalls***). Without such caution, the analyst may misrepresent the value of the DNA results. The analyst should further reiterate to the end-user the reporting caveats and limitations and remind them to consider the results within the context of all case information (see ***Appendix 5.1***).

5.8 Take-Home Messages for the End-Users of DNA Reports

The recommendations contained in this chapter reflect the EWG's views on how to improve the way that DNA results and comparisons are reported. DNA results could mislead an investigation if end-users and factfinders do not consider other case information such as an alibi or a reasonable explanation for the DNA profile to be present. The potential to mislead an end-user or factfinder will be greatly reduced if they understand the caveats and limitations associated with the DNA results.

The factors discussed in this chapter are especially important in situations where an analyst may not be given the opportunity to explain their results in more detail, such as during charging decisions, pre-trial negotiations, and plea agreements. Due to the risk of misunderstanding a DNA result that is reported inappropriately, it is a matter of both ethics and professionalism to ensure that analysts properly convey the value of DNA and other biological results.

These are the key take-home messages for end-users and factfinders:

- FSSPs should craft the DNA report to contain enough information that an end-user should be able to understand what was done, by whom, for what purpose, what results the analysis produced, and what these results do and do not mean.

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- The FSSP that issued the report can assist the end-user in understanding the DNA report, and the FSSP is best equipped to provide training.
- End-users should feel encouraged to contact the FSSP if they do not understand the DNA report.
- The end-user should be aware that the reporting analyst must be careful in how they represent the results in all communications about the DNA analysis. Reporting analysts cannot provide an opinion on the proposition nor the issue(s) at hand. The reporting analyst must only provide an opinion on the results given the propositions.
- The function of reporting analysts and factfinders are distinct. The reporting analyst provides a result; the factfinder puts that result in the context of all the other evidence.
- FSSPs should provide end-users with the caveats and limitations of the analysis, results, interpretations, and opinions. If the DNA report does not clearly state them or where to find them, the end-user should ask for them.
- DNA results should not be used in isolation. End-users must understand DNA results in the context of the whole case, and FSSPs should encourage this understanding by providing reporting caveats and engaging in regular training sessions with end-users.
- If the end-user of the report does not properly understand the value and expression of the DNA results, its misuse can lead to a miscarriage of justice. FSSPs should emphasize the importance of assisting end-user comprehension of a DNA report.

Appendix 5.1: Example Caveats and Limitations to Include in a Report

The following table consists of a non-exhaustive list of example reporting caveats and limitations to include when communicating DNA results.

Reason for the Caveat or Limitation	Example of Reporting Caveat or Limitation
Communication through email correspondence	Unlike results and analysis conveyed in official reports, email communications conveying this information have not been technically reviewed to assure precise language.
An alert on the importance of case information	Since the evaluation presented in this report is dependent on the information provided and the propositions formed using this information, any change in the case information used to inform the propositions should be seen as a sufficient reason for a new evaluation. If any of the information changes, or if new, relevant information is made available, contact the FSSP to reevaluate the results as soon as possible.
Underline the distinction between explanations of results and propositions	The explanations of the DNA results provided aim to inform the investigation in the absence of a POI. The list of explanations offered may not be exhaustive or mutually exclusive and must not replace the need to consider formal propositions once there is a POI. Any reports or opinions offered once a POI is determined supersede these explanations.
An alert about CODIS investigative leads	An investigative lead generated as a result of a DNA database search was obtained between Item 1 and POI. A reference from the POI must be submitted for direct comparison and statistical analysis. Using the DNA investigative lead alone has the potential to be misleading. It is important to evaluate the DNA lead in conjunction with the other available evidence.
Alert on the biological sex information provided	Biological (DNA-based) sex information aims to inform the investigation and should not be misinterpreted to mean that an individual must also appear as male or female based upon this indication alone. Furthermore, this information does not confirm that a specific cell type is present or imply how or when the DNA was deposited. Amelogenin shows only a peak X; as such, the profile appears to come from one individual and was reported as female. The investigative information reported by the FSSP regarding male or female contributors is based solely upon the assessment of the DNA types at locations on the X and Y chromosomes. One explanation for the reported results is that the biological sex of the contributor is female and therefore consistent with what was reported. Another explanation could be that this contributor has had a deletion in amelogenin and appears to be female for this DNA location only due to analytical reasons. There may be other explanations. There are also situations where an individual's gender expression and sex chromosome types may not necessarily align. Therefore, this information should be viewed with caution given the exceptions.
Alert that the end-user needs to request supplementary materials such as bench notes and electronic data if	The report does not contain all the documentation associated with the work performed or the content necessary to understand and evaluate all the work performed. Independent analysis and interpretation of the data requires a review of the full case record.[361]

[361] National Commission on Forensic Science. *Recommendation to the Attorney General Documentation, Case Record, and Report Contents*. 2016. https://www.justice.gov/archives/ncfs/page/file/905536/download.

Reason for the Caveat or Limitation	Example of Reporting Caveat or Limitation
applicable (see ***Sec. 6.3: Discovery and Disclosures***)	
General description of how NOC is assigned	The true number of contributors of DNA to an item can never be known. The number of contributors for each DNA profile is assigned given the quantity and quality of the information detected as well as the relationship between the peaks detected. Additional information such as item type and known contributors may also aid in the assignment of the number of contributors.
General description of suitability determination	Decisions about the suitability for comparisons to all or a portion of a DNA profile are made prior to the comparison to any reference profiles unless case circumstances support conditioning on a known contributor. Regarding an assignment of number of contributors above the forensic science service provider's validated range for interpretation will render the entire DNA profile not suitable for comparison.
Convey that differential extraction results must not be interpreted as an opinion on the presence or absence of semen	Items containing the [chosen differential extraction] suffixes were subjected to a differential extraction (i.e., an extraction method which attempts to separate non-sperm cell DNA [suffix 1] from sperm cell DNA [suffix 2] to create two fractions). If an abundance of either cell type is present, a mixture may result in one or both fractions. The use of a differential extraction method and the subsequent detection (or not) of male DNA alone does not support the inference regarding the presence or absence of semen.
Convey and justify why a reporting cap was used	When the assigned LR exceeds the reporting cap of 1 billion, it will be reported as "of the order of 1 billion." The LR reporting cap of 1 billion was chosen because of the limitations of biostatistical modeling and independence assumptions of STR loci as referenced by Hopwood et al., 2012 and Foreman and Evett 2001.
Alert that profile descriptors cannot be applied to activity-level issues	DNA profiles may be described as major, minor, component 1, or with differential extraction suffixes for analytical reasons; however, these descriptors should not be interpreted in the context of a decision regarding the nature of the material or the mechanisms, actions, or timing that led to the deposition of the DNA.
Convey the limitations of an *exclusion*	Results suggesting that a particular POI should be excluded as a possible contributor to a DNA sample must be interpreted within the context of the case. There could have been an error in the process, or the absence of DNA of this person from the material may need to be assessed in the context of the case by considering factors such as the persistence and recovery of DNA.
Convey that DNA results cannot be interpreted as the analyst providing an opinion regarding who the source of the DNA is	This report and evaluation do not directly answer who the source of the DNA is. Rather, the reported results may help answer questions about the source by providing an evaluation of the results in light of the propositions (i.e. "The POI is the source of the DNA" versus "An unknown individual is the source of the DNA"). This assessment of the DNA results should be integrated with other case information and evidence by the end-user, which is not considered to be part of the DNA analyst's task. DNA evidence evaluations should not be used as the sole evidence to completely rule out any one view (i.e., proposition). The biological results must be considered within the context of all information and evidence available in the case. This decision is outside of the role of the DNA analyst.

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Reason for the Caveat or Limitation	Example of Reporting Caveat or Limitation
LRs cannot speak to the likelihood of a proposition, only to the probability of the results given a pair of propositions	A likelihood ratio indicates if, and to what extent, the DNA analysis results support one proposition over another. It is not possible on this basis alone to determine which is the most probable proposition. To assign the probability of a proposition, the DNA analysis results should be combined with other information in the case. This is not considered to be the role of the DNA analyst.
Convey that DNA statistics cannot imply uniqueness within a population	Based on DNA results only, even when presented with a reference to a local or world population, scientists cannot opine whether a POI is the source of the DNA or not.
Alert on the difference between source-level and activity-level issues	This report does not provide any information on the mechanisms or actions that led to the deposition or absence of the recovered biological material. It only provides information that may help inform its origin (e.g., who is the source of the DNA).
Delineate the meaning of a verbal qualifier	The likelihood ratio is a numerical value. Words can be assigned to brackets of numerical values and used to describe the extent of the support that the results provide for a proposition (over another). Several verbal equivalence tables have been published, and they are above all, a convention.[362]
Convey that a new evaluation cannot be performed on the witness stand	Testimony cannot be given regarding evaluations that were not provided in the report or documented in the case file. If the issue changes (e.g., the source of the DNA is no longer contested, a relative of the POI needs to be considered, or the issue pertains to how or when the DNA was deposited), a new evaluation will be needed in advance of the trial.

[362] Gill P, Hicks T, Butler JM, Connolly E, Gusmao L, Kokshoorn B, Morling N, van Oorschot RAH, Parson W, Prinz M, Schneider PM, Sijen T, Taylor D. DNA Commission of the International Society for Forensic Genetics: Assessing the Value of Forensic Biological Evidence - Guidelines Highlighting the Importance of Propositions: Part I: Evaluation of DNA Profiling Comparisons Given (Sub-) Source Propositions. *Forensic Science International: Genetics*. 2018; 36:189-202. doi:10.1016/j.fsigen.2018.07.003.

6. Pre-Trial Preparation and Testimony

6.1 Introduction and Scope

Offering clear and accurate testimony is an essential part of the DNA *experts*'[363] role in the criminal justice system. Because the factfinder determines how much weight to give the biological results in deciding the case, testimony should enable the factfinder to suitably use the DNA results and experts' opinion in their decision-making. To this end, experts must testify within the bounds of their scientific and technical expertise.

The Expert Working Group (EWG) explored research on effective communication, the limits of human cognition, and how laypeople understand different forms of testimony. We also explored the bounds of scientific expertise and ways that DNA analysts might express DNA comparison results in a way that could understate the limits of the science or amount to giving an opinion on topics that are in the remit of the factfinders.

We considered these research findings within the context of the United States legal system, and they are presented in this chapter along with examples concerning:

- Appropriate pre-trial and testimony communications regarding DNA results
- The expert's role of communicating evaluations of DNA results given at least two mutually exclusive propositions, as formulated considering case information
- Common testimony pitfalls and approaches to help prevent misstatements that could impact judicial outcomes
- Expressing limitations and caveats associated with DNA analysis

This chapter's topics closely relate to those in ***Chapter 4: Quantitative and Qualitative Ways to Express DNA Results*** and ***Chapter 5: Reporting***. For a discussion on testimony as it relates to serological screening results, see ***Sec. 4.6: Interpretation and Expression of Serological Screening Results***.

Legal rules and practices concerning testimony vary between jurisdictions. Some experts may also be bound by specific licensing or oversight body rules regarding testimony. This chapter provides only general guidance and is specific to providing testimony on DNA comparison results (i.e., sub-source-level DNA results in the hierarchy of propositions; see ***Sec. 3.2.1.1: The Importance of Case Assessment and Information***). It is important to consult with appropriate oversight bodies, criminal justice partners, and forensic science service provider (FSSP) counsel regarding the applicable governing laws for a specific FSSP's jurisdiction.

[363] DNA *analyst* is frequently replaced with *expert* in this chapter, as this term has a specific legal meaning in the context of providing testimony.

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The intent of the guidance provided is to assist experts in identifying and advocating for communications to further the goal of the appropriate use of science to achieve fair, just, and accurate resolutions. To achieve this goal, it is imperative that FSSP management support scientific or technical experts by providing dedicated time for analysts to develop oral presentation skills (see also ***Sec. 10.7.1*: Individual, Team, and Organizational Learning**).

6.2 General Considerations for Expert Testimony

Rule 702 of the Federal Rules of Evidence (FRE) provides in part that "a witness who is qualified as an expert by knowledge, skill, experience, training or education may testify in the form of an opinion or otherwise."[364] Most state-level rules regarding expert evidence employ the same or similar language. Testimony by a DNA expert should assist the factfinder's understanding and evaluation of the meaning and appropriate value to be given to the DNA results.

The basic tenets of expert testimony include qualifications, reliability, relevance, impartiality, clarity, and consistency. Appropriate testimony should:

1. Be reflective of, and supported by, written reports and case records.
2. Accurately convey the results of examinations, observations, interpretations, conclusions, and opinions, as well as provide additional information in response to questioning from criminal justice partners or the court.
3. Present information in a clear, complete, and impartial manner.
4. Explain the meaning of the results within the context of the task-relevant information that informed the analysis.
5. Present the limitations of biological results and DNA comparisons relevant to the methods used to produce the opinion being testified to.
6. Whenever possible, use language that is easy for laypeople to understand.

Only those personnel qualified and authorized to present an opinion should do so (see ***Sec. 6.7*: Establishing the DNA Analyst as an Expert During Testimony**). International Organization for Standardization/International Electrotechnical Commission (ISO/IEC) 17025:2017 specifies that "when opinions and interpretations are expressed, the laboratory shall ensure that only personnel authorized for the expression of opinions and interpretations release the respective statement."[365] Although ISO standards may only formally apply to experts in ISO-accredited FSSPs, the EWG recommends that all experts follow this guidance or comply with the principal goals the standards are intended to address.

[364] Federal Rule of Evidence. *FRE 702 Testimony by Expert Witnesses*. 2011. https://www.law.cornell.edu/rules/fre/rule_702.

[365] International Organization for Standardization (ISO). *General Requirements for the Competence of Testing and Calibration Laboratories, ISO/IEC 17025:2017*. 2017. https://www.iso.org/standard/66912.html. See 7.8.7.1.

The adversarial nature of the United States criminal justice system is not always aligned with the scientific community's goals when it comes to testifying. Scientists are tasked with presenting the most complete and accurate information relating to any scientific opinion being offered. Attorneys, however, operate under their own set of legal and ethical obligations and interests, which are distinct from and sometimes opposed to those of science (see **Callout Box 6.1**).

Moreover, experts cannot control the ultimate perceptions factfinders may have about the offered testimony. As expressed by Stoney, "the courtroom is not a scientific arena." He posits that "it's important that we use the scientific criteria for evidence, but the law has built a system that is based on personal, subjective human judgment. So, I can testify, and the jury can decide they didn't like the way I looked or responded to questions and dismiss me entirely."[366]

While frustrating, the control that expert witnesses have is undeniably limited. Despite this, experts should always attempt to provide clear and accurate information concerning complex DNA and statistical concepts in response to the questions posed.

Expert opinions communicated during testimony should be supported by thorough, written reports and complete records of any analyses conducted (see ***Chapter 5*: *Reporting***). Whenever legally possible and permissible, analysts should participate in pre-trial meetings or consultations with *all* parties to mitigate potential misunderstandings of their findings (see ***Sec. 6.4*: *Pre-Trial Communication***).

Callout Box 6.1: How the Adversarial Process Impacts DNA Analysts and Interpretation of DNA Results

When experts are called to assist in legal matters, the environment of the legal system will always, to some degree, influence testimony. In countries that operate under an adversarial legal system, the prosecuting party and defendant "face off" during the pre-trial and court proceedings. Each side presents evidence to support their "theory of the case." To do this, each side will frame the evidence in a different way and may supplement it with narrative that they believe will convince the factfinder.

The party requesting the services of the DNA analyst may color the analyst's approach or testimony in a phenomenon called adversarial allegiance.[367] Consider a situation where the prosecution has asked for a DNA expert to write a report and testify in a sexual assault case. The prosecution is asking the DNA expert to weigh in on whether the DNA from the sexual assault kit (SAK) came from the defendant or not. The information that they provide to the analyst and the framing of their request may influence the analyst.

Furthermore, the factfinder may interpret the expert's testimony considering the arguments made by the side that called them. So, even balanced or neutral comments might be interpreted in a biased manner. This effect might be similar when the defense calls a DNA expert.

[366] National Institute of Justice (NIJ). The Slow but Steady March Towards a More Reliable Forensic Science. Accessed March 27, 2024. https://nij.ojp.gov/topics/articles/slow-steady-march-towards-more-reliable-forensic-science.

[367] Murrie DC, Boccaccini MT. Adversarial Allegiance among Expert Witnesses. *Annual Review of Law and Social Science*. 2015; 11:37-55. doi:10.1146/annurev-lawsocsci-120814-121714.

6.3 Discovery and Disclosures

Although legal knowledge and interpretations are not within FSSPs' areas of expertise, FSSPs need some understanding of attorneys' discovery and disclosure obligations. Knowing these obligations, they can contemplate the type of information attorneys might seek, as well as information that might not be requested and yet necessary to disclose.

The discussions within this chapter are not intended as a legal primer or to substitute for the assessments of the parties. Additionally, some jurisdictions may have professional codes of responsibility or other provisions requiring FSSPs to anticipate potential obligations relating to disclosures. For example, the Texas Code of Professional Responsibility applicable to licensed forensic personnel and management for accredited FSSPs states that FSSP management shall:[368]

> Ensure the laboratory's forensic disclosure policy provides clear instructions for identifying and disclosing any exculpatory, impeachment, or mitigating document, item, or information in the possession, custody, or control of the laboratory. The policy should explicitly address how to inform potentially affected recipients of any non-conformances or breaches of law or ethical standards that may adversely affect either a current case or a previously issued report or testimony.[369]

Discovery refers to the pre-trial phase where the parties involved in the case produce or gather information to prepare for trial. During discovery, disclosures are required so that a party will have the necessary information to adequately prepare for trial. Discovery and disclosure help to promote transparency, reduce the likelihood of surprises during trial, and increase the chances of a fair and just outcome.

There are also instances where attorneys may have continuing obligations after case dispositions that involve FSSPs (see ***Sec. 2.6*: *The Duty to Correct or Report Errors and Adverse Events***). Attorneys should advise the FSSP of any discovery or disclosure obligations. These obligations may include the production of case files or case records, general laboratory documents, and specific information about the expert or the FSSP.

[368] Texas Administrative Code: 37. *§651.219. Code of Professional Responsibility*. 2020. http://txrules.elaws.us/rule/title37_chapter651_sec.651.219.

[369] To better enable FSSPs to achieve disclosure compliance, some states have passed laws requiring FSSPs to participate in statewide laboratory electronic discovery portals and have provided funding for implementation. The goal is to assist FSSPs with technology modernization and improve access for legal end-users. See, e.g., Texas Government Code. *Chapter 411: Department of Public Safety of the State of Texas*. 2023. https://statutes.capitol.texas.gov/Docs/GV/htm/GV.411.htm. § 411.162.

Prosecuting attorneys have specific constitutional disclosure obligations under *Brady v. Maryland*,[370] as well as under various statutes and rules.[371] While these obligations typically belong to the prosecutor, experts must provide requested information, and in some instances information that is not requested, to assist the prosecutor in meeting discovery or disclosure obligations. Depending on the jurisdiction, there may also be general statutory or discovery rule obligations for the defense.[372]

Ideally, every prosecutor's office would have a disclosure compliance policy, or an executed memorandum of understanding, to share with FSSP management or other experts. Likewise, defense attorneys should communicate any statutory or ethical obligations imposed on the defense to their experts. These communications can explain and memorialize what is required from the FSSP to enable the attorneys to comply with their obligations.[373]

During pre-trial preparation, both attorneys and FSSPs should attempt to identify any underlying data, case files, or other information that may require specific additional disclosure rather than limiting inquiries to only information contained in the report.[374]

Attorneys do not typically have the same scientific knowledge as a DNA expert, and therefore may not understand the reported opinions. Furthermore, they may not have the full materials that support these opinions. Attorneys may request disclosure of these materials and the FSSP should have guidance to ensure they disclose the necessary materials. Some non-exhaustive examples that may, or may not, be requested by the attorneys but may be of interest to them include:

- Unsatisfactory internal or external proficiency tests[375]

[370] United States Supreme Court. *Brady v. Maryland, 373 U.S. 83*. 1963.

[371] American Bar Association. *ABA Standards for Criminal Justice: Discovery, Fourth Edition*. PART II Discovery Obligations of The Prosecution and Defense. 2020. https://www.americanbar.org/groups/criminal_justice/standards/discovery-fourth-edition/; Texas Code of Criminal Procedure. *Chapter 39. Discovery. §39.14*. 2021. https://texas.public.law/statutes/tex._code_of_crim._proc._article_39.14.

[372] American Bar Association. *ABA Standards for Criminal Justice: Discovery, Fourth Edition*. PART II Discovery Obligations of The Prosecution and Defense. 2020. https://www.americanbar.org/groups/criminal_justice/standards/discovery-fourth-edition/; Texas Code of Criminal Procedure. *Chapter 39. Discovery. §39.14*. 2021. https://texas.public.law/statutes/tex._code_of_crim._proc._article_39.14.

[373] Cornell Law School Legal Information Institute. Federal Rule 16. Discovery and Inspection. 2021. https://www.law.cornell.edu/rules/frcrmp/rule_16; Massachusetts State Police Crime Laboratory. Laboratory Materials Request Policy. Accessed March 27, 2024. https://www.mass.gov/doc/laboratory-materials-request-policy-0/download; Texas Code of Criminal Procedure. *Chapter 39. Discovery. §39.14*. 2021. https://texas.public.law/statutes/tex._code_of_crim._proc._article_39.14.

[374] Gross SR, Possley MJ, Roll KJ, Stephens KH. *Government Misconduct and Convicting the Innocent: The Role of Prosecutors, Police and Other Law Enforcement*. University of Michigan Law School. 2020. https://repository.law.umich.edu/cgi/viewcontent.cgi?article=1165&context=other; United States Supreme Court. *Brady v. Maryland, 373 U.S. 83*. 1963.

[375] New York Criminal Procedure Law. *CPL Article 245*. Accessed March 27, 2024. https://ypdcrime.com/cpl/article245.php. *See* 245.20(1)(f) which includes "a list of proficiency tests and results administered or taken within the past ten years of each expert witness whom the prosecutor intends to call as a witness at trial or a pre-trial hearing."

- Laboratory self-disclosures to accrediting or oversight bodies[376]
- Confirmed systemic errors identified by or reported to the FSSP
- Instances of conflict resolution of differing analyst interpretation conclusions[377]
- Nonconformities (e.g., contamination events, quality incidents)

6.4 Pre-Trial Communication

Pre-trial communications encompass all forms of communication occurring outside of the courtroom setting. This section focuses primarily on pre-trial communications via in-person or remote meetings.

Regardless of the expertise of the attorneys or experts, pre-trial preparation should, at a minimum, include a discussion about the DNA results in advance of trial. It is the experience of members of the EWG that pre-trial meetings do not always occur, and that when they do, they may not be thorough enough or may not occur early or often enough.

Although the DNA expert cannot always control the existence or extent of pre-trial communications, it is important for experts to attempt to obtain pre-trial meetings with, at a minimum, the sponsoring party. An email upon receipt of a subpoena that includes language suggesting available dates for a pre-trial meeting is one way to encourage a pre-trial meeting.

FSSPs may also consider adopting standard language for reports, email communications, or subpoena confirmations explaining that pre-trial communications are necessary. This standard language should articulate that in some instances, pre-trial communications will be required if the party intends to engage in any questioning beyond the scope of the reported results and opinions. It should also convey that, in general, an expert cannot provide testimony on opinions that were not disclosed in the report or the supporting case file documentation (see ***Appendix 5.1***).

DNA experts also cannot control how attorneys and factfinders will ultimately use or argue the value of DNA results, opinions, or expert testimonies. Regardless, it is critical that experts exercise every opportunity to avoid being complicit in the intentional and unintentional misuse of these results, opinions, or testimonies. To that end, DNA analysts have a duty to clearly communicate the value and limitations of biological interpretations and opinions offered to attorneys and other criminal justice partners *prior* to trial (see also ***Sec. 9.7: Criminal Justice Partner Education***). In

[376] Ibid. *See* 245.20(1)(j) which includes "any preliminary or final findings of non-conformance with accreditation, industry or governmental standards or laboratory protocols."

[377] Ibid. *See* 245.20(1)(j) which includes "any conflicting analyses or results by laboratory personnel regardless of the laboratory's final analysis or results."

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doing so, end-users have the best opportunity to properly understand and subsequently use and communicate the value and limitations of that evidence.

If end-users or factfinders misunderstand or inadequately communicate scientific evidence and opinions, they can contribute to erroneous outcomes or the need for retrials.[378] Therefore, *all parties* have a responsibility to promote comprehension of DNA evidence and ensure its proper use in the courtroom.

FSSPs and DNA experts should encourage and support an environment where the value of communicating with all parties is clearly understood by both the sponsoring and opposing party. If necessary, sponsoring attorneys and experts can establish the parameters of permissible communication with the opposing party prior to communications occurring.

Ideally, pre-trial communications would occur between the DNA expert(s) and all attorneys involved in the case. It is critical that both sides have access to the experts performing examinations, reporting conclusions, and offering opinions on that information. Both sides should also have access to those individuals who performed laboratory work (if different from the reporting analyst) and analysts who performed the technical reviews of the DNA examinations, results, and opinions. Despite this, pre-trial meetings or discussions with the defense are often less common than those with the prosecution.

Additionally, defense experts are typically restricted from communicating with the state because of confidentiality. Some jurisdictions[379] allow for pre-trial depositions of witnesses, which is a formal process to communicate expert opinions in advance of trial. However, other jurisdictions provide for limited, if any, defense disclosures via deposition or otherwise.

When depositions do occur, they may offer some protection by confirming that an expert intends to testify within their area of expertise, based upon appropriate data. Depositions also allow all parties to determine if additional experts may be needed for the applicable and relevant evidence to be admitted. However, aside from uncommon exceptions (e.g., conditional examinations granted by a judge), most jurisdictions do not provide for deposition practice in criminal law.

Typically, the prosecution's obligations of disclosure increase the possibility that the analyst will be able to discuss the case with the defense. However, even this communication may have

[378] Gill P. Misleading DNA Evidence: Reasons for Miscarriages of Justice. *International Commentary on Evidence*. 2012; 10(1):55–71. doi:10.1515/ice-2014-0010; Gross SR, Possley MJ, Roll KJ, Stephens KH. *Government Misconduct and Convicting the Innocent: The Role of Prosecutors, Police and Other Law Enforcement*. University of Michigan Law School. 2020. https://repository.law.umich.edu/cgi/viewcontent.cgi?article=1165&context=other; Morgan J. Wrongful Convictions and Claims of False or Misleading Forensic Evidence. *Journal of Forensic Sciences*. 2023; 68(3):908-61. doi:10.1111/1556-4029.15233.

[379] The exact number of states that require pre-trials is likely relatively low; however, research was not performed to determine the laws of each state. Examples of "deposition" states are Florida, Michigan, and Minnesota.

nuanced considerations or restrictions that an expert without legal expertise would be unable to assess alone.

6.5 Pre-Trial Material Preparation

Robust pre-trial preparation helps ensure attorneys understand the methods used, the expert's opinions, and how the expert assigned the value of the DNA results (e.g., likelihood ratio [LR] or Random Match Probability [RMP]). This level of preparation also increases the potential for attorneys to pose questions that could resolve ambiguities or confusion. The following sections describe the specific materials attorneys and experts may want to discuss prior to trial to develop a shared comprehension of the results.

6.5.1 Bench Notes and Other Data Used to Inform DNA Expert Opinion

Pre-trial preparation by the attorney(s) and expert(s) should include the review of bench notes and other data used to form opinions and may include the review of other FSSP documents. FSSPs should consider providing attorneys with a table of contents to assist in navigating this material, as the amount of information provided upon discovery can be overwhelming. FSSPs can also identify what information they might not routinely provide but can make available upon request—such as validation and electronic (e.g., quantitation data, electropherograms) materials.

6.5.2 Statistical Testimony

Statistical calculations can be difficult to understand. Correct and frequent articulation of applicable statistical calculations by the analyst in the presence of the attorney can help familiarize the attorney with the important concepts and terms. Correcting an attorney's misstatement or misunderstanding of statistical calculations or concepts during pre-trial communications minimizes the risk of the attorney carrying the misunderstanding forward into trial. Providing or directing attorneys or other end-users to training opportunities may also help build a shared understanding of evidence.

6.5.3 Demonstrative Exhibits

Demonstrative exhibits can help establish the foundation of DNA testimony in a more engaging manner than purely verbal communications alone.[380] Demonstrative aids may be tailored to the specific case to reflect any caveats and limitations of DNA testing.

Pre-trial communications between the expert and the attorney can assist in formulating questions that the expert may be able to answer using demonstrative exhibits (see ***Sec. 6.11.3*:**

[380] Park J, Feigenson N. Effects of a Visual Technology on Mock Juror Decision Making. *Applied Cognitive Psychology*. 2012; 27(2):235-46. doi:10.1002/acp.2900; Summers K, Wyler H. Impact of In-Depth Information and Multimedia Presentation on Mock Jurors' Comprehension of Mitochondrial DNA Evidence. *Forensic Science International: Mind and Law*. 2022; 3:100072. doi:10.1016/j.fsiml.2022.100072.

Technique #3: Use Visual or Demonstrative Aids). However, it is critical that demonstrative aids not created by the expert are provided to the expert well in advance of trial, so they have time to thoroughly review and correct them to accurately reflect the results or concepts to be conveyed. Consideration should also be given to having FSSP-generated demonstratives reviewed by another analyst for accuracy prior to providing them to the attorneys.

6.5.4 Additional Propositions and Considering New Information

Pre-trial meetings also provide attorneys the opportunity to ask about the underlying scientific principles of forensic DNA interpretation, explore the assigned number of contributors (NOC), consider the propositions formulated, and understand the statistical calculations used. It may be appropriate to propose reasonable alternate propositions based on additional or changed information. For example, the additional collection of a reference sample for a consensual intimate partner enables the analyst to condition on this individual—requiring a new evaluation.

There may also be assumptions that are no longer appropriate once new case information is relayed and which would require a new evaluation (e.g., a previously unknown relative of the Person of Interest [POI]) should now be considered—see ***Sec. 3.5.4: Considering Relatives*** and ***Sec. 3.6: Post-Comparison Interpretation: Modifying an Interpretation After a Comparison***). Another example supporting the need for new evaluations is the circumstance where there are multiple POIs—sometimes referred to as the two-suspect problem.[381] In this instance, the analyst may need to decide if the previous approach was appropriate and whether to consider functionally exhaustive propositions by conditioning on each POI.[382]

Furthermore, the analyst may have assigned several LR values based upon different proposition pairs in the case notes or report. The analyst should reiterate to the attorneys that the most meaningful way to assist the factfinder is to present an LR for each POI.[383] In some situations, it

[381] Gill P, Haned H. A New Methodological Framework to Interpret Complex DNA Profiles Using Likelihood Ratios. *Forensic Science International: Genetics*. 2013; 7(2):251-63. doi:10.1016/j.fsigen.2012.11.002; Gittelson S, Kalafut T, Myers S, Taylor D, Hicks T, Taroni F, Evett IW, Bright JA, Buckleton J. A Practical Guide for the Formulation of Propositions in the Bayesian Approach to DNA Evidence Interpretation in an Adversarial Environment. *Journal of Forensic Sciences*. 2016; 61(1):186-95. doi:10.1111/1556-4029.12907; Taylor D, Buckleton J, Evett IW. Testing Likelihood Ratios Produced from Complex DNA Profiles. *Forensic Science International: Genetics*. 2015; 16:165-71. doi:10.1016/j.fsigen.2015.01.008.

[382] Hicks T, Kerr Z, Pugh S, Bright JA, Curran JM, Taylor D, Buckleton J. Comparing Multiple POI to DNA Mixtures. *Forensic Science International: Genetics*. 2021; 52:102481. doi:10.1016/j.fsigen.2021.102481.

[383] Gill P, Hicks T, Butler JM, Connolly E, Gusmao L, Kokshoorn B, Morling N, van Oorschot RAH, Parson W, Prinz M, Schneider PM, Sijen T, Taylor D. DNA Commission of the International Society for Forensic Genetics: Assessing the Value of Forensic Biological Evidence - Guidelines Highlighting the Importance of Propositions: Part I: Evaluation of DNA Profiling Comparisons Given (Sub-) Source Propositions. *Forensic Science International: Genetics*. 2018; 36:189-202. doi:10.1016/j.fsigen.2018.07.003.

is helpful to consider if both POIs together are the source of the DNA mixture versus if two unknown individuals are.[384]

Due to the complexity of the evaluations and the requirements of the quality assurance (QA)/quality control (QC) and technical review processes, the most appropriate time for an analyst to adjust or perform additional analyses based on new information is in advance of trial. To the extent that the results need to be assessed given new information and propositions, it is necessary for attorneys to provide the analyst with advanced notice of any proposition changes so that the new evaluation can undergo proper technical review (see ***Sec. 6.9.1: Testifying to an Evaluation That Is Not in the Report or Case File***).

6.5.5 Questions About How or When the DNA Was Deposited

Pre-trial meetings provide a crucial opportunity for DNA analysts to reiterate that DNA comparisons—in isolation—do not answer questions about how or when the DNA was deposited. Analysts can explain that the DNA comparisons do not address the possibility of any suggested transfer scenario intended to explain the presence or absence of a POI's DNA (see ***Sec. 6.12: Staying in Your Lane: Avoiding Common Testimony Pitfalls***).

The expert should discuss the following considerations if the questions in the case have shifted from source to activity:

- If neither party is contesting the source of the DNA, the statistical value should not be a focus of the presentation.
- If testimony is still offered, the expert should communicate that the value of the DNA comparison (the LR or RMP) does not apply to questions regarding the disputed activities (see ***Chapter 7: How and When Questions in DNA Analysis***).[385]
- The scientist must explain that it is not possible to say whether the transfer was more likely direct or indirect.[386]

[384] For example, consider a situation where an alleged sexual assault occurred in a park and a condom is found at the scene. The results are a mixture of DNA in which both the POI and complainant's individual LRs are greater than 1. An LR is assigned considering that both the POI and complainant are the source of the DNA mixture or that two unknown individuals are. This LR is less than 1; the results give more support to the second proposition than the first.

[385] Cook R, Evett IW, Jackson G, Jones PJ, Lambert JA. A Hierarchy of Propositions: Deciding Which Level to Address in Casework. *Science & Justice*. 1998; 38(4):231-9. doi:10.1016/S1355-0306(98)72117-3; European Network of Forensic Science Institutes (ENFSI). *ENFSI Guideline for Evaluative Reporting in Forensic Science: Strengthening the Evaluation of Forensic Results across Europe (STEOFRAE), Version 3.0*. 2015. https://enfsi.eu/wp-content/uploads/2016/09/m1_guideline.pdf; Gill P, Hicks T, Butler JM, Connolly E, Gusmao L, Kokshoorn B, Morling N, van Oorschot RAH, Parson W, Prinz M, Schneider PM, Sijen T, Taylor D. DNA Commission of the International Society for Forensic Genetics: Assessing the Value of Forensic Biological Evidence - Guidelines Highlighting the Importance of Propositions. Part II: Evaluation of Biological Traces Considering Activity Level Propositions. *Forensic Science International: Genetics*. 2020; 44:102186. doi:10.1016/j.fsigen.2019.102186; Jackson G, Biedermann A. "Source" or "Activity" What Is the Level of Issue in a Criminal Trial? *Significance*. 2019; 16(2):36-9. doi:10.1111/j.1740-9713.2019.01253.x.

[386] Gill P, Hicks T, Butler JM, Connolly E, Gusmao L, Kokshoorn B, Morling N, van Oorschot RAH, Parson W, Prinz M, Schneider PM, Sijen T, Taylor D. DNA Commission of the International Society for Forensic Genetics: Assessing the Value of Forensic Biological Evidence - Guidelines Highlighting the Importance of Propositions. Part II: Evaluation of Biological Traces Considering Activity Level Propositions. *Forensic Science*

6.5.6 *Communicate Other Relevant Details*

During pre-trial communications, it could be helpful for attorneys to inform experts about the outcome of motions in which certain parts of DNA testimony may not be admissible. These meetings also allow analysts to discover additional relevant instructions that may be specific to the case or the court. Examples of these include the desired use of a pseudonym by a complainant or victim when their legal name is in the expert's report, prohibitions on references to DNA database leads, or limitations on referencing expert witness notes during testimony.

Pre-trial discussions also allow the attorney and expert to consider and discuss whether the expert will be needed to assist with any motions filed or observe other experts' testimonies. These important logistic considerations assist in preparing the expert for the varied court experiences that can occur as a function of the jurisdiction, participants, and rules or agreements that may exist. Otherwise, experts often discover these particulars for the first time on the stand.

Analysts should also consider discussing quality incidents during pre-trial communications to ensure all parties understand the extent of the incidents and can make informed decisions on the need to address those during trial. In some instances, there may be individuals better suited to discussing the intricacies of the QA/QC process than the DNA expert (e.g., supervisor, Technical Leader [TL], QA/QC manager). Analysts should identify those individuals to criminal justice partners during pre-trial communications.

Recommendation 6.1: When legally permissible and possible, the testifying DNA analyst and the legal professionals involved in the case should confer prior to the trial to gain a shared understanding of the report, propositions, correct language for describing the value of the results, and what the results mean and do not mean.

6.5.7 *Testifying When the Method Is No Longer Best Practice*

Given the extended time it can take for cases to proceed through the criminal justice system, it is inevitable that an expert may testify to DNA results which were reported with procedures that are no longer in use or recommended as best practice. For example, the expert should consider how to approach questions regarding the "identification" of a biological material or source attribution of the DNA regarding the defendant if the FSSP was providing those opinions during the time that a report was written. For this example, the expert should consider following the

International: Genetics. 2020; 44:102186. doi:10.1016/j.fsigen.2019.102186; Gill P, Hicks T, Butler JM, Connolly E, Gusmao L, Kokshoorn B, Morling N, van Oorschot RAH, Parson W, Prinz M, Schneider PM, Sijen T, Taylor D. DNA Commission of the International Society for Forensic Genetics: Assessing the Value of Forensic Biological Evidence - Guidelines Highlighting the Importance of Propositions: Part I: Evaluation of DNA Profiling Comparisons Given (Sub-) Source Propositions. *Forensic Science International: Genetics*. 2018; 36:189-202. doi:10.1016/j.fsigen.2018.07.003.

current best practices by providing an opinion on the results—not a statement of certainty about the nature of the biological material or the source of the DNA.

How to proceed in these situations must be evaluated based upon the professional and ethical duties of the expert as well as what is defined in their FSSP's procedures. FSSP procedures should consider when it is appropriate to issue a new report for older cases proceeding to trial (e.g., reinterpretation with probabilistic genotyping software [PGS] when original report had Combined Probability of Inclusion [CPI]), how to support former employees who may still be giving expert witness testimony on behalf of the FSSP, and notifying end-users of a change in technology or best practice to alert when aspects of testimony would no longer be considered best practice. Any actions taken, and the rationale for these actions, should be discussed with all affected parties during pre-trial.

6.6 Pre-Trial Admissibility Hearings

An admissibility hearing is a proceeding in which the judge assesses the admissibility of proposed evidence to determine whether the methodologies used were reliable, valid, and appropriately applied (or, in some jurisdictions, simply whether they are generally accepted in the relevant scientific community). The appropriate witness(es) for an admissibility hearing will depend on the challenges to the proffered evidence and testimony, the attorneys' preferences, and the applicable admissibility standard for the jurisdiction. Other experts besides (or possibly instead of) the reporting DNA analyst may need to testify.

These proceedings are often referred to as *Daubert* or *Frye* hearings. *Daubert* and *Frye* are prominent cases on the standards for admissibility relevant to expert testimony.[387] There are applicable state cases that may be referenced by name as well. Federal courts follow the Federal Rules of Evidence—especially FRE 702—when evaluating the admissibility of expert testimony.[388] States have the same or similar rules of evidence, although interpretations of rules can vary.

Courts considering admissibility of evidence under the *Daubert* standard typically look to the non-exhaustive factors outlined by the Supreme Court majority opinion in *Daubert v. Merrell Dow Pharmaceuticals, Inc.* to assess whether the methodology underlying the testimony is scientifically valid.[389] These factors are:

1. Whether the theory or technique can be (and has been) tested
2. Whether the theory or technique has been subjected to peer-review and publication

[387] District of Columbia Court of Appeals. *Frye v. United States 293 F. 1013*. 1923. ; United States Supreme Court. *Daubert v. Merrell Dow Pharmaceuticals (92-102), 509 U.S. 579*. 1993.

[388] Federal Rule of Evidence. *FRE 702 Testimony by Expert Witnesses*. 2011. https://www.law.cornell.edu/rules/fre/rule_702.

[389] United States Supreme Court. *Daubert v. Merrell Dow Pharmaceuticals (92-102), 509 U.S. 579*. 1993.

3. The known or potential rate of error
4. The existence and maintenance of standards controlling the theory or technique's operation
5. The degree of acceptance within a relevant scientific community

While a few jurisdictions still operate under the *Frye* standard, where a court inquires whether the methodology employed is "generally accepted" in the relevant scientific community,[390] most jurisdictions have adopted the *Daubert* standard.[391]

Admissibility-hearing witnesses should be familiar with both developmental and internal validations of the method or technology. Witnesses should also be familiar with published research on the methodology and the theory or theories behind it. Experts and attorneys might also want to be familiar with the FSSP's accreditation standards, Federal Bureau of Investigation's Quality Assurance Standards (FBI QAS),[392] and relevant guidelines such as those issued by the Scientific Working Group on DNA Analysis Methods (SWGDAM), The Organization of Scientific Area Committees for Forensic Science (OSAC), and the International Society for Forensic Genetics (ISFG).

When addressing the testability factor of *Daubert*, it is imperative for the analyst to demonstrate that the theory or technique used was tested under circumstances that apply to the case at hand. The expert testimony presented at pre-trial admissibility hearings may include the FSSP's Technical Leader or validation coordinator or an expert outside the FSSP who possesses research, development, or validation expertise.

Since the party proffering the evidence bears the burden of demonstrating reliability or general acceptance, that party and the expert should be prepared to demonstrate that internal validation involved ground-truth-known samples that are representative of the types of samples the analyst interprets in their casework and, preferably, also in the case at hand (see ***Sec. 8.3*: Scientific Quality and Standardization**). Ideally, the expert will be well-versed in the FSSP's approach to internal validation of the method or technology at issue.

The witness must also have knowledge of the practices within the relevant scientific community. This may include the practices of FSSPs across the country, practices internationally, and information published in peer-reviewed scientific journals. Non-forensic disciplines may also use

[390] Cornell Law School Legal Information Institute. Frye Standard. Updated December 2022. Accessed March 26, 2024. https://www.law.cornell.edu/wex/frye_standard.

[391] Perhaps with variation, see Kaye DH, Bernstein DE, Mnookin JL. *The New Wigmore: A Treatise on Evidence - Expert Evidence*. 3rd ed. Wolters Kluwer Law & Business: 2020.

[392] Federal Bureau of Investigation (FBI). *Quality Assurance Standards for Forensic DNA Testing Laboratories*. 2020. https://le.fbi.gov/file-repository/forensic-qas-070120.pdf/view.

the same method. For example, mitochondrial DNA (mtDNA) sequencing is used in clinical medicine as well as in forensic science.

Testifying experts should prepare for admissibility hearings by meeting or talking with the party sponsoring the evidence and testimony at issue to determine the scope of the hearing. Together, the testifying expert and sponsoring party should also determine whether additional experts may be helpful to establish the **developmental validation** aspects of the theory or technique used.

6.7 Establishing the DNA Analyst as an Expert During Testimony

An expert is typically introduced in court by describing the education, training, and experience that has led them to gain expertise on the relevant subject. Witnesses proffered as experts may also undergo a "voir dire" during trial to satisfy the judge that they are qualified to give scientific or other expert testimony, or they may have their qualifications examined in pre-trial or ancillary proceedings held outside the presence of a jury.

The expert may be asked about the following information during the qualification process:

- Undergraduate, graduate, or postgraduate academic work and performance
- Components and rigor of the forensic DNA analysis training program required for casework authorization
- Casework activities (e.g., years of experience, extent of work performed)[393]
- Contributions made to field-relevant research or publications
- Teaching experience or experience training others in the same or relevant discipline(s)
- Membership in professional organizations and attendance at professional meetings
- Participation in other continuing education opportunities, either DNA-specific (e.g., required by the FBI QAS or applicable certifying body) or as required for state-level licensure

Qualification as an expert, however, does not mean the individual is qualified to offer opinions on all aspects of forensic DNA. For instance, an expert may have training and experience regarding the communication of the value of biological results given DNA comparisons (e.g., do the DNA results support the POI as the source of the DNA rather than an unrelated individual?). This does not mean the same expert is automatically qualified to render an opinion, for example,

[393] United States Department of Justice. *Uniform Language for Testimony and Reports for Forensic Autosomal DNA Examinations Using Probabilistic Genotyping Systems*. 2022. https://www.justice.gov/olp/page/file/1095961/dl. Specific to the issue of establishing expertise of forensic DNA experts in court, the DOJ's ULTR cautions analysts against citing the number of forensic autosomal DNA examinations performed in an analyst's career as a direct measure for the accuracy of a proffered conclusion, but it does allow analysts to cite this information when establishing, defending, or describing their qualifications.

about another expert's results regarding the value of a Y-chromosome short tandem repeat (Y-STR) comparison.

Courts should closely examine the formal education, training, and experience of an analyst to determine the specific areas of forensic DNA in which the analyst qualifies as an expert and ensure that those qualifications correlate to the testimony being offered. Rigorous direct and cross examination, or testimony on complex types of DNA analysis, may increase the potential for experts to be (inadvertently) asked to provide opinions outside their expertise. Experts should be vigilant against answering questions outside their expertise, as courts and attorneys may not always recognize when specific questioning calls for testimony exceeding the limitations of the expert's scientific expertise.

6.8 Presenting Foundation and Limitations of Autosomal STR Testing

FSSPs should consider developing a process to standardize the language used to describe the results during testimony. For example, FSSPs should consider writing quality documents and offering training to provide guidance on what may be appropriate or inappropriate recitations during testimony.

Creating guidelines would enable the FSSP to incorporate recommended strategies for testimony preparation and communicating DNA results during testimony. Guidelines could also include recommended terminology for addressing complex questions about source attribution or activities. FSSPs or standards developing organizations (SDOs) should develop testimony-related standards; however, care should be taken not to make these too vague or overly prescriptive, which would not allow for the typical nuances encountered during testimony.[394]

The depth of background questions posed to the expert will vary. Answers to these background questions should be tailored to the demands of the case and detailed enough to educate the factfinder while still holding the factfinder's attention. These topics range from defining forensic DNA analysis and its purpose to stating the limitations associated with DNA results. Experts should also attempt to address incorrect notions about DNA analysis, such as the misperception that the methods and interpretations are flawless, and incorrect understandings about the concept of uniqueness associated with DNA technologies (see ***Sec. 2.5.1*: *Defining Error from a Human Factors Perspective***).

The expert's communication about what the DNA results do not mean is a vital aspect of DNA testimony, and the EWG recommends experts include the limitations of DNA analysis in their foundational or introductory testimony. Depending on the case circumstances, factfinders may

[394] Morrison GS, Neumann C, Geoghegan PH. Vacuous Standards — Subversion of the OSAC Standards-Development Process. *Forensic Science International: Synergy*. 2020; 2:206-9. doi:10.1016/j.fsisyn.2020.06.005.

also need to be aware of the limitations of DNA testing that pertain to the presence or absence of DNA and questions about transfer.

The expert must communicate that the value of DNA comparison results does not have a bearing on how and when the DNA was deposited. In addition, when considered in isolation, DNA results (e.g., presence, absence, quantity) cannot tell the factfinder when or how the DNA was deposited. The expert should avoid case-specific examples or jargon that the factfinder would not understand without substantial education.

The general concepts to cover during background or testimony may include:

- DNA techniques are sensitive and can detect trace amounts of DNA.
- The presence of DNA alone does not mean that an individual must have touched or had direct contact with that item or person.
- The absence of DNA alone does not mean an individual has not touched or had direct contact with an item or person.
- The expert cannot directly answer the question of *whose* DNA is on an item. However, the expert may be able to assist the factfinder by evaluating the probability of the DNA results considering if the POI is the source of the DNA versus if an unknown individual is the source of the DNA.
- DNA results are one part of all the evidence in the case.
- DNA comparison results cannot be used to answer questions about *how* or *when* the DNA was deposited or whether the transfer was direct or indirect[395] (see ***Chapter 7: How and When Questions in DNA Analysis)***.

[395] Gill P, Hicks T, Butler JM, Connolly E, Gusmao L, Kokshoorn B, Morling N, van Oorschot RAH, Parson W, Prinz M, Schneider PM, Sijen T, Taylor D. DNA Commission of the International Society for Forensic Genetics: Assessing the Value of Forensic Biological Evidence - Guidelines Highlighting the Importance of Propositions. Part II: Evaluation of Biological Traces Considering Activity Level Propositions. *Forensic Science International: Genetics*. 2020; 44:102186. doi:10.1016/j.fsigen.2019.102186. Gill P, Hicks T, Butler JM, Connolly E, Gusmao L, Kokshoorn B, Morling N, van Oorschot RAH, Parson W, Prinz M, Schneider PM, Sijen T, Taylor D. DNA Commission of the International Society for Forensic Genetics: Assessing the Value of Forensic Biological Evidence - Guidelines Highlighting the Importance of Propositions: Part I: Evaluation of DNA Profiling Comparisons Given (Sub-) Source Propositions. *Forensic Science International: Genetics*. 2018; 36:189-202. doi:10.1016/j.fsigen.2018.07.003.

Recommendation 6.2: When explaining the nature of DNA analysis during testimony, the DNA expert should address common misconceptions and state the limitations of the analysis. At a minimum, the DNA expert should address the following main points:

- **The DNA results are only part of the overall case.**
- **Errors can occur in any human process, including DNA analysis.**
- **The evaluation of the DNA comparison cannot conclusively identify an individual as the source of the DNA.**
- **DNA analysts cannot provide any information on how or when DNA was deposited in a particular case, based on a report considering only the source of the DNA.**

6.9 Testifying to Case-Specific Results

In response to questioning, the DNA expert should provide the factfinder with the results for each item tested. There may be legal or strategic reasons to omit the results for certain items (e.g., DNA database leads, evidence ruled inadmissible). The experts will not likely be privy to strategic reasons. Other information that may need to be communicated includes:

- The results of serology testing (see ***Sec. 4.6.3*: *Reporting and Testifying to Serology Results***)
- Reasons why the testing of certain samples was stopped prior to amplification
- The assigned NOC
- Reasons why the analyst determined the profile was unsuitable for comparisons

To assist factfinders' comprehension, the expert should use this portion of their testimony to supplement or fill in gaps regarding any important terms that may not have been adequately defined during the foundational portion of the testimony and reiterate definitions.

For testimony that pertains to the results of DNA comparisons, the expert should explain they can express the value of the DNA comparison which assists—but cannot alone answer—the question about who the source of the DNA is. This is true regardless of the type of statistic used in the case. When using an RMP/CPI, the expert will need to explain the two-step comparison process to account for the consideration of only one proposition (see ***Sec. 4.4*: *Other Quantitative Expressions of DNA Results***).

If the expert uses qualitative comparison terms during testimony, they must clarify that these descriptors are secondary to the accompanying numerical value of the DNA results. In other words, the "qualitative association" must be considered in tandem with the statistic when

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assigned. Without this spoken caveat, the factfinder may not fully understand the intent of the qualitative comparison.

When presenting an LR, the expert should explicitly state the two mutually exclusive propositions. This clearly communicates to the factfinder the opposing views about who the sources of DNA are. For example, the two propositions could be that (1) the DNA came from Mr. Smith or (2) the DNA came from an unknown, unrelated individual. Then, the expert should express the value of the DNA comparison, which explicitly contrasts the probability of the DNA results given the two propositions.

An attorney may ask the expert to only provide a qualitative term to describe the similarity between the evidence profile and POI profile. In this circumstance, the expert should state the statistics are necessary to express the value of the DNA comparison. Although it is the ethical and professional responsibility of the expert to attempt to provide the value of the DNA comparison, the court system may not permit this. See **Callout Box 6.2** for an example of how the expert can succinctly communicate the value of the DNA comparison to the factfinder.

Callout Box 6.2: Communicating the Value of the DNA Comparison to the Factfinder Using an LR

This example presentation of DNA results consists of propositions and the LR value in a manner that attempts to educate the factfinder on how to use the DNA results. To aid in factfinder comprehension, experts may consider substituting the term "proposition" or "hypothesis" with more understandable terms such as "points of view" or "scenario."

> *As I understood it, the question was whether the POI's DNA was on an item. I cannot answer that question directly, but what I can do is help by evaluating the DNA results based upon the following two points of view that consider who the source of DNA is:*
>
> *1) Mr. POI is the source of this DNA [or]*
>
> *2) An unknown, unrelated individual is the source of this DNA*
>
> *The DNA results from Item X are of the order of 1 billion times more probable if Mr. POI is the source than if an unknown, unrelated individual is.*
>
> *This calculation expresses the value of the DNA comparison between Mr. POI and Item X and shows the extent of support the DNA results provide for the first point of view versus the second point of view. Based upon these results alone, I cannot tell you that Mr. POI is the source of the DNA, as this is a disputed issue that does not only depend on the DNA results, but on all the other elements of the case. Therefore, it is for the court to decide on that issue.*
>
> *It is important to acknowledge that the DNA comparison does not help address any questions about how or when the DNA on Item X was deposited.*

See ***Appendix 5.1***.

Experts should only use verbal qualifiers—sometimes referred to as verbal equivalents—to supplement, not replace, the LR value. The expert should explain that the choice to use a verbal qualifier to further explain the value of the DNA comparison is a matter of convention and that

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there is no universal verbal scale, but, instead, several verbal scales exist that vary in their characterization of the strength or weakness of the statistic. The verbal scale is intended to provide some context to the scientific strength of the value of the evidence in words rather than numbers for ease of comprehension (see also ***Sec. 4.3.8*: Verbal Qualifier Statements Used to Supplement the LR)**.

If a quality incident (e.g., contamination, sample switch, nonconforming testing, resulting corrective actions) may have impacted a DNA result, comparison, or statistic, the DNA expert (or supervisor, TL, QA/QC manager) should discuss that during testimony.

6.9.1 Testifying to an Evaluation That Is Not in the Report or Case File

Generally, testimony should reflect the results contained in the formal report and associated case file that has been subjected to technical review. However, an attorney may want to elicit opinions based on information used for testing decisions that may or may not have been contained in the case file.

The DNA expert may be able to answer a limited number of questions from information contained within the case file such as communicating an LR when considering an untyped sibling in the alternative proposition. However, responses to many questions (e.g., changing the propositions) would require a reevaluation and technical review, which cannot be accomplished on the witness stand.

If an expert is asked to produce a new evaluation that is capable of being performed, the expert should clarify that the evaluation should be performed in the laboratory and technically reviewed prior to being offered during testimony. This guidance does not preclude the expert from using their knowledge, training, and experience to respond to questions; however, the expert should recognize when their opinions need to be supported by the FSSP's quality system.

Recommendation 6.3: DNA experts should not perform new evaluations of the DNA results on the witness stand because these evaluations have not been reviewed, reported, or disclosed to all parties.

6.10 Factors That Can Affect Laypersons' Perception of Scientific Testimony

When considering how to provide effective expert testimony, it is important to remember that testimony involves more individuals than just the expert testifying. The testifying expert is responsible for ensuring they provide accurate, complete, and digestible information. However, their ability to do this successfully depends on what questions the attorney asks.

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Effective expert testimony also requires that the attorney's questions and the expert's responses produce information the factfinder can understand and use. Although the expert has little control over most features of a trial, the guidance provided in this section aims to facilitate effective communication of the DNA findings regardless of these external considerations.

Experts need to balance communicating the DNA results accurately while also focusing on clarity so that the factfinder can understand and use the information. Accuracy discussions often focus on avoiding statements that transpose the conditional (see ***Sec. 6.12.1*: Properly Explaining the Quantitative Value of the Results**); however, overstatements or understatements of the evidence value are also inaccurate and perhaps more problematic. The expert's communication should be thorough, and they should clearly express the meaning of the results.

There are many factors that can increase the potential for error, bias, or understating/overstating when the expert communicates DNA results. First, most factfinders have a superficial understanding of what DNA evidence is and, as a result, may have already formed views about its reliability and probative value.[396] Physical evidence can also be particularly convincing—especially DNA evidence.[397] Add to this that jurors' existing beliefs about DNA analysis are typically informed by media coverage, entertainment platforms, social media, and other common sources of information.[398] These sources are typically not written or vetted by an expert, and sometimes might be mostly fictional (e.g., television shows like CSI: Crime Scene Investigation) or sensationalized (e.g., Netflix's Making a Murderer) for the purpose of entertainment, not accuracy.[399]

Thus, the sources of information that most individuals rely on present an incomplete picture of DNA analysis and what it can reliably achieve. As a result, laypersons typically remain unaware that DNA evidence can vary in quality or relevance to the ultimate issue in a case.[400]

Mock juror studies demonstrate a variety of factors that can influence laypersons' application of DNA testimony in their decision to convict or acquit—some that are ultimately irrelevant to the

[396] Schklar J, Diamond SS. Juror Reactions to DNA Evidence: Errors and Expectancies. *Law and Human Behavior*. 1999; 23(2):159-84. doi:10.1023/a:1022368801333.

[397] Garrett BL. *Autopsy of a Crime Lab: Exposing the Flaws in Forensics*. University of California Press: California, 2022. doi:10.2307/j.ctv1h9dkjv.

[398] Cole SA, Dioso-Villa R. Investigating the 'CSI Effect' Effect: Media and Litigation Crisis in Criminal Law. *Stanford Law Review*. 2008; 61:1335. doi:ssrn.com/abstract=1401417; Klentz BA, Winters GM, Chapman JE. The CSI Effect and the Impact of DNA Evidence on Mock Jurors and Jury Deliberations. *Psychology, Crime & Law*. 2020; 26(6):552-70. doi:10.1080/1068316x.2019.1708353; Schweitzer NJ, Saks MJ. The CSI Effect: Popular Fiction About Forensic Science Affects Public Expectations About Real Forensic Science. *Jurimetrics: The Journal of Law, Science, and Technology*. 2007; 47(3):357-64.

[399] Rodriguez L, Agtarap S, Boals A, Kearns NT, Bedford L. Making a Biased Jury Decision: Using the Steven Avery Murder Case to Investigate Potential Influences in Jury Decision-Making. *Psychology of Popular Media Culture*. 2019; 8(4):429-36. doi:10.1037/ppm0000192; Tassi P. Why 'Making a Murderer" Is Netflix's Most Significant Show Ever. *Forbes*. 2016. https://www.forbes.com/sites/insertcoin/2016/01/03/why-making-a-murderer-is-netflixs-most-significant-show-ever/?sh=163c6b9d326a

[400] Koehler JJ, Schweitzer NJ, Saks MJ, McQuiston DE. Science, Technology, or the Expert Witness: What Influences Jurors' Judgments About Forensic Science Testimony? *Psychology, Public Policy, and Law*. 2016; 22(4):401-13. doi:10.1037/law0000103; Shelton DE. The 'CSI Effect': Does It Really Exist? Accessed March 27, 2024. https://nij.ojp.gov/topics/articles/csi-effect-does-it-really-exist.

quality of the evidence or the testimony. For example, in one study, mock jurors were more likely to convict if complex DNA evidence was presented by a female expert compared to a male expert.[401]

Statements about the years of experience and educational background of an expert can also effect mock jurors' decisions about how much weight to give the evidence presented.[402] Moreover, this type of information seems to outweigh other useful information that is more relevant to the reliability and accuracy of the DNA evidence—these more general pieces of information had a larger effect on mock jurors than other kinds of information that was more specific to the forensic evidence, such as laboratory accreditation or certification.[403] Mock jurors will also be influenced by the side that presents the DNA evidence.[404]

Studies examine whether mock jurors are influenced by information regarding the potential for error in the forensic expert's opinion.[405] One such study reported that "[w]hen the expert offered a match statistic without acknowledging the risks that diminish its probative value (i.e., coincidence, mix-ups, and examiner error), jurors were generally more persuaded by the evidence than they were when the expert offered objectively stronger evidence (i.e., evidence that did account for the various risks)."[406]

A study examining mock jurors' application of knowledge about the potential for bias in the forensic expert's opinion found that participants tended to discount the expert's testimony if the expert admitted that their opinion could have been influenced by contextual information. However, when the analyst simply stated that they were not vulnerable to bias because of their training and experience, individuals tended to believe the analyst, even though research shows that training and experience cannot immunize people against cognitive bias.[407]

The extent to which these methods influence factfinders' beliefs is mixed, but presenting an opposing expert witness and providing error rates as part of the testimony generally tend to be

[401] Maeder EM, McManus LA, McLaughlin KJ, Yamamoto S, Stewart H, Walla P. Jurors' Perceptions of Scientific Testimony: The Role of Gender and Testimony Complexity in Trials Involving DNA Evidence. *Cogent Psychology*. 2016; 3(1):1264657. doi:10.1080/23311908.2016.1264657.

[402] McCarthy Wilcox A, NicDaeid N. Jurors' Perceptions of Forensic Science Expert Witnesses: Experience, Qualifications, Testimony Style and Credibility. *Forensic Science International*. 2018; 291:100-8. doi:10.1016/j.forsciint.2018.07.030.

[403] Ibid.

[404] Maeder EM, Ewanation LA, Monnink J. Jurors' Perceptions of Evidence: The Relative Influence of DNA and Eyewitness Testimony When Presented by Opposing Parties. *Journal of Police and Criminal Psychology*. 2016; 32(1):33-42. doi:10.1007/s11896-016-9194-9.

[405] Garrett BL, Crozier WE, Grady R. Error Rates, Likelihood Ratios, and Jury Evaluation of Forensic Evidence. *Journal of Forensic Sciences*. 2020; 65(4):1199-1209. doi:10.1111/1556-4029.14323; Koehler JJ. If the Shoe Fits They Might Acquit: The Value of Forensic Science Testimony. *Journal of Empirical Legal Studies*. 2011; 8(s1):21-48. doi:10.1111/j.1740-1461.2011.01225.x.

[406] Koehler JJ. If the Shoe Fits They Might Acquit: The Value of Forensic Science Testimony. *Journal of Empirical Legal Studies*. 2011; 8(s1):21-48. doi:10.1111/j.1740-1461.2011.01225.x. p. 39.

[407] Kukucka J, Hiley A, Kassin SM. Forensic Confirmation Bias: Do Jurors Discount Examiners Who Were Exposed to Task-Irrelevant Information? *Journal of Forensic Sciences*. 2020; 65(6):1978-90. doi:10.1111/1556-4029.14546; Thompson WC, Scurich N. How Cross-Examination on Subjectivity and Bias Affects Jurors' Evaluations of Forensic Science Evidence. *Journal of Forensic Sciences*. 2019; 64(5):1379-88. doi:10.1111/1556-4029.14031.

equal in successfully drawing attention to these issues.[408] As a result, it may be difficult to convince factfinders, or even an individual with a scientific (non-forensic) background,[409] that it is possible for a forensic expert to misrepresent the evidence or make a mistake. It is imperative that DNA analysts provide information about the potential for error and bias in a way that can be understood and appropriately applied by a non-expert audience.[410]

6.11 Improving Verbal Communication During Testimony

Many of the recommendations for improving written communication (see ***Chapter 5: Reporting***) also apply to oral communication. Making use of research-based techniques in conjunction with practice and regular feedback can improve an analyst's ability to describe their results to individuals involved in the criminal legal process and, as a result, increase confidence in their ability to communicate analytical processes and findings.

6.11.1 Technique #1: Avoid Jargon as Much as Possible

Analysts (and attorneys) should aim to describe analyses and results in plain language as much as possible.[411] Even though forensic science jargon is the most accurate description to use when discussing evidence with fellow analysts, the goal of testimony is to ensure the factfinder understands the DNA results. This goal can be difficult to achieve using words factfinders do not understand. For instance, although the word 'proposition' is commonly used among analysts, this word may have a different meaning for the non-expert.

Some ways to avoid the problems associated with jargon use include:

- **Providing a definition at the first use of a jargon term.** For example:

  I considered the propositions based on the information I received. "Proposition" is a specific term used by analysts but can also be thought of as hypotheses or proposed scenarios. You will hear me use this word throughout my testimony as a shorthand way to describe the scenarios I considered. I evaluated the DNA evidence based upon these propositions, or scenarios.

[408] Eastwood J, Caldwell J. Educating Jurors About Forensic Evidence: Using an Expert Witness and Judicial Instructions to Mitigate the Impact of Invalid Forensic Science Testimony. *Journal of Forensic Sciences*. 2015; 60(6):1523-8. doi:10.1111/1556-4029.12832; Mitchell G, Garrett BL. Battling to a Draw: Defense Expert Rebuttal Can Neutralize Prosecution Fingerprint Evidence. *Applied Cognitive Psychology*. 2021; 35(4):976-87. doi:10.1002/acp.3824.

[409] Koehler JJ. The Influence of Prior Beliefs on Scientific Judgments of Evidence Quality. *Organizational Behavior and Human Decision Processes*. 1993; 56(1):28-55. doi:10.1006/obhd.1993.1044.

[410] Eastwood J, Caldwell J. Educating Jurors About Forensic Evidence: Using an Expert Witness and Judicial Instructions to Mitigate the Impact of Invalid Forensic Science Testimony. *Journal of Forensic Sciences*. 2015; 60(6):1523-8. doi:10.1111/1556-4029.12832; Mitchell G, Garrett BL. Battling to a Draw: Defense Expert Rebuttal Can Neutralize Prosecution Fingerprint Evidence. *Applied Cognitive Psychology*. 2021; 35(4):976-87. doi:10.1002/acp.3824.

[411] Howes LM, Kemp N. Discord in the Communication of Forensic Science: Can the Science of Language Help Foster Shared Understanding? *Journal of Language and Social Psychology*. 2016; 36(1):96-111. doi:10.1177/0261927x16663589.

- **Using the jargon term the first time the attorney or expert introduces the concept and explaining it by using the substituted term from that point on (e.g., "scenario" rather than "proposition").** This strategy can reduce cognitive load and increase processing ease the most effectively, as the factfinder will no longer need to remember, understand, and apply the new term every time it is used by the expert. This may be a valuable technique when the expert knows it will not be possible to avoid the jargon term.
- **Replacing a complex narrative statement with plain language narrative.** For example:

  Complex Narrative Statement: *"Evaluative reporting shall consist of a clear statement of the propositions—formulated through circumstances of the case and between parties in the criminal justice system expressed by the magnitude of the likelihood ratio."*

  Plain Language Narrative Statement: *"Analysts formulate the pertinent points of view—then the evidence is evaluated given each point of view. The statistical value indicates the degree of support the evidence provides for one point of view versus the other."*

As with most other testimony situations, the use of these techniques and their value will vary and may depend on the length and complexity of the testimony, pre-trial interactions with attorneys regarding potential questioning, and the intuitiveness of the term being used.

6.11.2 Technique #2: Make It Easier for the Factfinder to Process the Information

The factfinder is presented with so much information throughout a trial, some of which is complex, technical, or unfamiliar. Experts can improve their communication by helping the audience focus on and retain the most important aspects of their testimony.[412]

When communicating to a non-expert audience, some strategies for making complex information easier to process include:[413]

- **Providing reminders about information presented earlier when referenced again**. For example:

  Earlier (or previously) we discussed the second sample found on the bathroom floor. I explained that [insert]. This is similar to/the same as/like the current example/topic because [explain].

[412] Krcmar M, Ewoldsen DR, Koerner A. *Communication Science Theory and Research: An Advanced Introduction*. Routledge: New York, NY, 2016.

[413] Mayer RE, Moreno R. Nine Ways to Reduce Cognitive Load in Multimedia Learning. *Educational Psychologist*. 2010; 38(1):43-52. doi:10.1207/s15326985ep3801_6; Unkelbach C. The Learned Interpretation of Cognitive Fluency. *Psychological Science*. 2006; 17(4):339-45. doi:10.1111/j.1467-9280.2006.01708.x.

- **Speaking clearly and at an appropriate cadence, volume, and inflection.** The expert should consider repetition of the main take-home messages, especially if the testimony is lengthy.
- **Organizing responses and keeping them concise.** The expert should avoid poorly organized and long-winded answers, which are more difficult for the factfinder to understand and remember.
- **Taking time to consider the question before answering.** Experts can respond with "*That's an interesting question—please give me a moment to think it through*," to prevent misstatements that could follow from rapid responses.
- **Clarifying confusing questions before attempting to answer them.** If the expert is confused by the question, the factfinder is likely to also be confused. In these instances, the expert should seek clarification rather than attempting to answer based on a potentially inaccurate interpretation of the question.

6.11.3 Technique #3: Use Visual or Demonstrative Aids

Presenting visual or demonstrative information in addition to oral testimony can be very effective for improving, understanding, and recalling the content of the testimony.[414] Common examples include PowerPoint presentations that educate the factfinder on DNA analysis and tables that summarize the DNA results.

Tables that summarize DNA results should not include presentations of complete DNA allele tables. This is necessary to prevent potential miscommunications by attorneys or factfinders who may rely on these rather than reports or testimony (see ***Sec. 5.5.6*: Additional Information to Consider Including in a DNA Report**). It also helps discourage attorneys and factfinders from performing their own (and likely inaccurate) comparisons.

Demonstratives should be used to keep track of large amounts of complex information and should focus on the main point. It is important to limit the use of visual information that might be emotionally inflammatory to factfinders (e.g., crime scene photos) because such materials (which may also prompt objections) can increase negative and retributive feelings and bias the factfinder to be more punitive.[415]

Demonstrative trial exhibits, including excerpts from a report, are best prepared by the testifying expert. If an exhibit is prepared by an individual other than the expert, it is important that it be provided to the expert in advance of trial for review and verification of the demonstrative's accuracy. If the expert is not given the exhibit in advance of trial, the expert should relay at trial

[414] Sweller J. Cognitive Load Theory, Learning Difficulty, and Instructional Design. *Learning and Instruction*. 1994; 4(4):295-312. doi:10.1016/0959-4752(94)90003-5.

[415] Bright DA, Goodman-Delahunty J. Gruesome Evidence and Emotion: Anger, Blame, and Jury Decision-Making. *Law and Human Behavior*. 2006; 30(2):183-202. doi:10.1007/s10979-006-9027-y.

that they are unable to use the exhibit without first verifying the accuracy of its contents and request a recess when necessary to properly review it.

To use demonstratives effectively, the visual information content should be simple. Simple bulleted lists, diagrams, figures, or images (e.g., of the item collected that has been tested for DNA) are ideal, as they contain basic, important aspects of the testimony. Using these techniques can help capitalize on the benefits of demonstrative information while avoiding overloading or distracting the factfinder. More research is needed to understand the potential positive and negative impact of dynamic slides with animations or video.[416]

6.12 Staying in Your Lane: Avoiding Common Testimony Pitfalls

Improper expert testimony can contribute to miscarriages of justice.[417] For example, if an expert unintentionally testifies in a way that misrepresents the evidence, it can lead the factfinder to an unwarranted overassessment or underassessment of that evidence.

The factfinder must answer the ultimate question of guilt or innocence considering *all* the evidence that is presented in the case. So, how does an expert testify in a manner allowing the factfinder to appropriately consider the DNA evidence in conjunction with all other evidence the factfinder has found to be probative? To accomplish this, the expert must focus on the value of the DNA comparison results given the proposition(s). This is the expert's lane of expertise. By staying in this lane, the expert is best positioned to assist the factfinder while minimizing the risk of misleading the factfinder or providing erroneous testimony.

6.12.1 Properly Explaining the Quantitative Value of the Results

Consistently and correctly expressing the value of DNA results is one of the biggest challenges of DNA testimony. When the expert strays from discussing the DNA results given the propositions and instead provides an opinion on the proposition (e.g., it is the POI's DNA), they have transposed the conditional.[418] No matter the type of statistical analysis method used (e.g., LR, RMP), the expert cannot directly answer the question of whose DNA is on an item based solely on the DNA results (see ***Sec. 4.2*: Why DNA Analysts Should Not Make Source Attributions**).

The expert and attorneys should avoid the common pitfall of relating the numerical value of the DNA comparison to the size of the local, state, or world populations. For example, consider an

[416] Park J, Feigenson N. Effects of a Visual Technology on Mock Juror Decision Making. *Applied Cognitive Psychology*. 2012; 27(2):235-46. doi:10.1002/acp.2900; Summers K, Wyler H. Impact of In-Depth Information and Multimedia Presentation on Mock Jurors' Comprehension of Mitochondrial DNA Evidence. *Forensic Science International: Mind and Law*. 2022; 3:100072. doi:10.1016/j.fsiml.2022.100072.

[417] Gill P. Misleading DNA Evidence: Reasons for Miscarriages of Justice. *International Commentary on Evidence*. 2012; 10(1):55–71. doi:10.1515/ice-2014-0010.

[418] Evett IW. Avoiding the Transposed Conditional. *Science & Justice*. 1995; 35(2):127-31. doi:10.1016/S1355-0306(95)72645-4; Hicks T, Buckleton J, Castella V, Evett IW, Jackson G. A Logical Framework for Forensic DNA Interpretation. *Genes (Basel).* 2022; 13(6):957. doi:10.3390/genes13060957.

RMP of 1 in 1 million. It would be correct to state that in a population of 1 million, the expert would *expect on average* to observe one person (in addition to the POI) with a genotype that is the same as the evidence profile. However, it would be incorrect to state that this expected number is equal to the actual number, which is referred to as the *expected value or uniqueness fallacy*.[419]

Consider flipping a fair coin 10 times. Although the average value of obtaining a "head" is five; the actual number of observed heads in successive trials of 10 flips will vary between zero and ten. To assert that there could only be one individual in a population of one million who could be the contributor of the DNA just because the RMP is one in a million is to misunderstand the relationship between probabilities and average values. The probability that there will be more than one individual with that profile in a population of one million when the RMP is one in a million is appreciable.

Another common fallacy is called the *defense attorney's fallacy*.[420] It involves assigning a very small probability of the POI being the source, based on the size of the relevant population and the RMP. With an RMP of 1 in 1 million, the expert would be correct to state that in a population of 10 million, they would *expect on average* to observe 10 people in each population with a genotype that is the same as the evidence profile. The defense attorney's fallacy is to reason that the DNA findings are worthless because there could be some 10 other people with the same profile. However, a profile that reduces a population of possible sources from 10 million people to only 10 or so is surely relevant.

Additional complications can arise when experts are asked to explain the statistical calculation in a way that deviates from their previous testimony or reporting. An attorney's recitations of the expert's statement about the results can be especially problematic. For example, an attorney may paraphrase the expert's testimony incorrectly while trying to reiterate or simplify the results for the factfinder.

An attorney may also ask questions or make statements that associate the probability assigned to the question about whether the POI is or is not the source of the DNA. It is the expert's responsibility to answer these questions in a way that does not lead the factfinder to undervalue or overvalue the DNA results.

[419] Kaye DH. The Expected Value Fallacy in State v. Wright. *Jurimetrics: The Journal of Law, Science, and Technology*. 2011; 51(4):1921082. doi:ssrn.com/abstract=1921082.

[420] Thompson WC, Newman EJ. Lay Understanding of Forensic Statistics: Evaluation of Random Match Probabilities, Likelihood Ratios, and Verbal Equivalents. *Law and Human Behavior*. 2015; 39(4):332-49. doi:10.1037/lhb0000134; Thompson WC, Schumann EL. Interpretation of Statistical Evidence in Criminal Trials: The Prosecutor's Fallacy and the Defense Attorney's Fallacy. *Law and Human Behavior*. 1987; 11(3):167-87. doi:10.1007/bf01044641.

Often, expert responses require more than "yes" or "no," and responding as such to misstated inquiries can leave out necessary details. For example, the expert may not appreciate how simply removing "DNA results" from a statement can easily convert an appropriate evaluative statement into an incorrect transposed conditional. **Callout Box 6.3** expands on this issue and provides guidance on how to avoid giving erroneous opinions regarding DNA results.

Callout Box 6.3: How to Avoid Transposing the Conditional

The expert must communicate their results in a manner that only expresses the nature of the findings presented and does not overstep their role into the domain of the factfinder. As such, the expert should avoid transposing the conditional.

The expert cannot provide an opinion about the source of the DNA based only upon their results since they do not have all the case information. Although these issues are subtle, the following tips may help the expert:[421]

- Look for the "if" or "given" part of the statement and ensure that the *findings* come before the "if" and that the *proposition* is the thing being conditioned on after the "*if*."
- Ensure that the probability of the findings is evaluated under both hypotheses.
- Scrutinize statements that include a "that" or just one "than." For example, "The probability that the profile came from an individual other than the POI is 1 in 1 billion" is a transposed conditional.
- If unsure, rephrase the statement, making sure to phrase it in terms of the probability of the *results given propositions* and not the *probability of the proposition given the results*. Then, help the factfinder understand the difference between these and what the evidence *does not* imply. Stating plainly what an LR *is not* can also assist the factfinder's understanding.
- It is helpful to begin the sentence with "The DNA results are …"

Finally, some statements use verbal qualifiers that should be carefully phrased (see ***Sec. 4.3.8*: *Verbal Qualifier Statements Used to Supplement the LR***). For example, the statement "The results provide very strong support for the proposition that the defendant is the source of the DNA as opposed to the proposition that an unknown, unrelated individual is the source of the DNA" is appropriate because the statement is about the value of the results and references both propositions.

However, conditioning (i.e., a "given" statement) on the results is problematic. For example, a statement like "Given the results, it is my testimony that it is more likely that the defendant contributed to the sample than an unknown, unrelated individual did" is a statement about the probability of the proposition given the DNA evidence rather than the probability of the evidence given the proposition.

Consider the examples below comparing incorrect statements an analyst may encounter during communication of the results to the corresponding corrected statements. While the incorrect statement discusses propositions in reference to the results, the correct statement discusses the value of the results in reference to the two propositions. The expert must focus the opinion on the results and never make statements about the probability or likelihood of the propositions themselves:

[421] Buckleton J, Bright JA, Taylor D. *Forensic DNA Evidence Interpretation*. 2nd ed. CRC Press: Boca Raton, 2016. doi:10.4324/9781315371115; Evett IW. Avoiding the Transposed Conditional. *Science & Justice*. 1995; 35(2):127-31. doi:10.1016/S1355-0306(95)72645-4; Hicks T, Buckleton J, Castella V, Evett IW, Jackson G. A Logical Framework for Forensic DNA Interpretation. *Genes (Basel)*. 2022; 13(6):957. doi:10.3390/genes13060957.

Incorrect Statement *Bold emphasis used to show problematic phrasing	Corrected Statement *Bold emphasis used to show appropriate phrasing
It is 1 million times more probable **that** the DNA originated from the POI than from an unknown, unrelated individual. Why this is incorrect: The opinion is about the proposition instead of the results.	**The DNA profile** is 1 million times more probable to be observed **if** the DNA originated from the POI **than if** it originated from an unknown, unrelated individual. **or** It is 1 million times more probable to observe the DNA profile **if** the POI is the source of the DNA **than if** an unknown, unrelated individual is the source of the DNA.
There is only a 1 in 1 million chance that an unknown individual that is unrelated to the POI is the source of the DNA. Why this is incorrect: The opinion is about the proposition instead of the results.	**The probability of seeing the DNA profile** is 1 in 1 million **if** an unknown individual that is unrelated to the POI is the source of the DNA.
Given the DNA results, it is a million times more likely **that** the DNA is from the POI than from an unknown, unrelated individual. Why this is incorrect: The statement conditions (i.e., "given the DNA results") on the results instead of the proposition.	**The results** are a million times more probable **if** the DNA is from the POI rather **than if** it is from an unknown, unrelated individual.

Situations where transposing the conditional produces large differences in the probabilities are easy to imagine. **Figure 6.1** is a graphical depiction of the following text:

> The probability of an animal with four legs (the evidence) given that it is the dog, Fido (the proposition) is 1, assuming Fido has four legs. This is the probability of the evidence given the hypothesis, P(E|H). However, the converse probability P(H|E) that a particular animal is Fido given that it has four legs (the evidence) is close to zero. These are very different probabilities because there are so many four-legged animals that are not Fido to consider. This example demonstrates the importance of conditioning. Conditioning on the proposition (i.e., an animal with four legs | Fido) gives one probability. Conditioning on the observation (i.e., Fido | an animal with four legs) gives a radically different probability.

How does this translate to DNA testimony? Consider the following scenario: DNA is found at the crime scene and Mr. Smith is a POI. An analyst evaluates the DNA from the item, as well as a DNA sample from Mr. Smith, and states "The DNA profile from the item found at the crime scene has an RMP of 1 in 100,000." There is no 'if' or 'given' in this statement. To begin to apply the RMP, the factfinder must rephrase it as "The probability of observing this profile given that the source of the DNA is an unknown, unrelated individual is 1 in 100,000."

This publication is available free of charge from: https://doi.org/10.6028/NIST.IR.8503

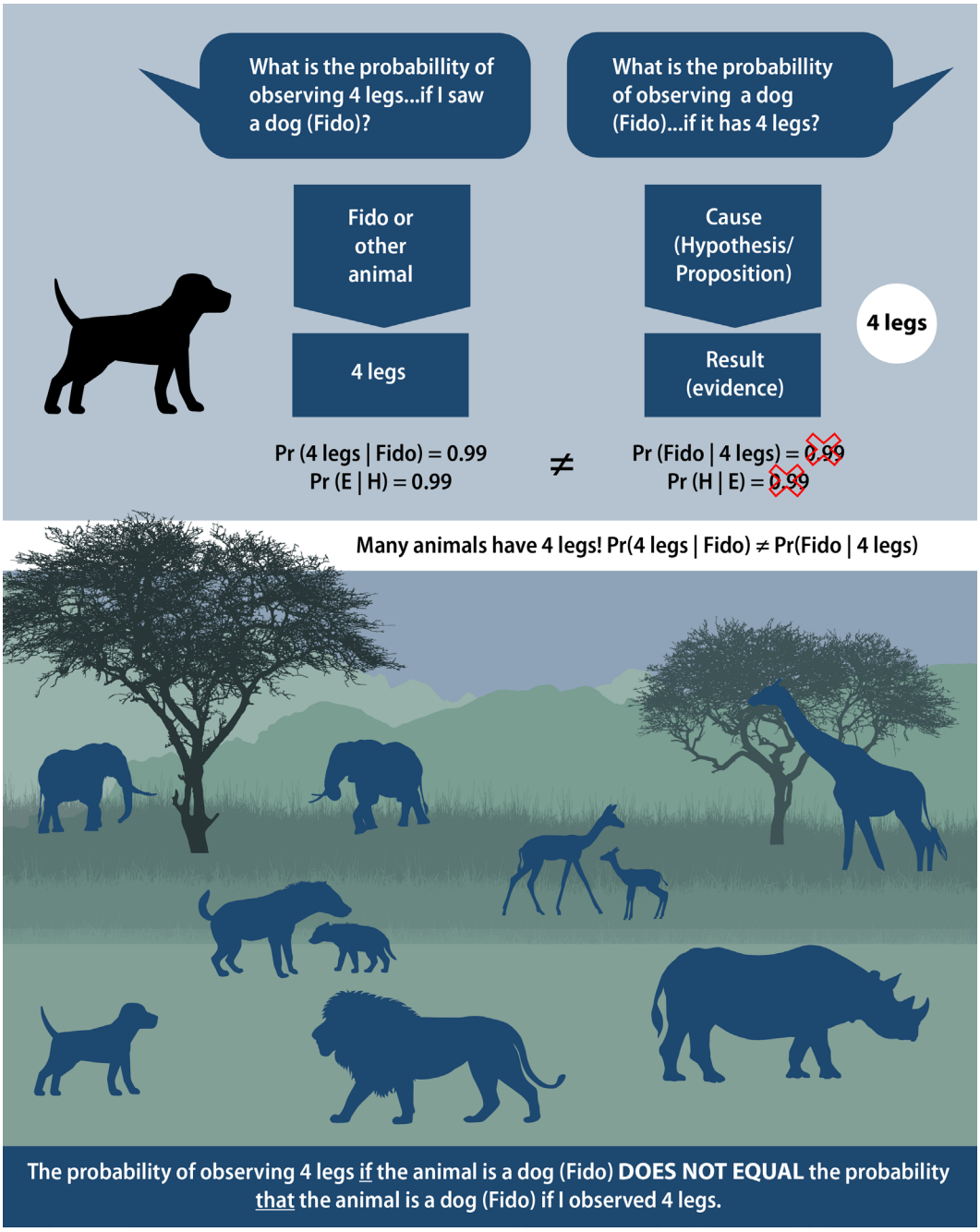

Figure 6.1: Graphical depiction of a transposed conditional.

Figure originally appeared in the University of Lausanne's Challenging Forensic Science Online Course and adapted with permission; Original illustrator: Antoine de Palma.[422]

Next, consider the question about the scenario that might be raised in court, "How likely is it that the DNA is from an unknown, unrelated individual and not from the defendant?" One might

[422] Coursera. Challenging Forensic Science: How Science Should Speak to Court. Accessed March 26, 2024. https://www.coursera.org/learn/challenging-forensic-science.

This publication is available free of charge from: https://doi.org/10.6028/NIST.IR.8503

answer that "The probability that an unknown, unrelated individual is the source of the DNA, given the observed profile, is .00001." While this sounds very similar to the previous statement about the probability of observing the profile, the two statements are not equivalent. More information would be required to compute this second probability because it is a posterior probability (see ***Sec. 4.3.2: Bayes' Theorem and Prior Odds***).

Consider again the example with Fido. If Fido is the only animal in the house, then, when the observer is at home, the observed four-legged animal is very likely to be Fido. On the other hand, when at a dog park filled with other animals, the chance that an observed four-legged animal is Fido decreases, as there are other four-legged animals who could be the source of these observed four legs.

6.12.2 What Can Be Said Now About How or When the DNA Was Deposited?

Typical DNA training programs focus on the competency and proficiency testing of analysts and the FSSP's procedures regarding questions about *whose* DNA is present. However, experts routinely encounter questions during testimony about *how* or *when* the DNA was deposited. What DNA analysts can say now about how and when the DNA was deposited is perhaps one of the most significant areas of concern raised throughout the EWG's discussions. For this reason, the EWG felt the topic warranted its own chapter (see ***Chapter 7: How and When Questions in DNA Analysis***). Of particular importance is **Table 7.1**, which presents examples of how DNA experts can respond during testimony to questions regarding how and when DNA was deposited.

6.13 Testimony Monitoring

Analysts should receive testimony training that prepares them to testify to the science of DNA analyses and the opinions contained within their DNA report. Even when testimony training and mock court exercises occur, it is difficult to predict the reality of the courtroom experience. Regardless, it is beneficial for DNA analysts to receive constructive critiques on their testimony performance. This feedback can assist in ensuring that the analyst is delivering quality testimony that conforms with FSSP expectations. Therefore, testimony monitoring is an important part of the FSSP's quality management system (QMS) and the endeavor for continual improvement (see ***Chapter 8: Quality Assurance/Quality Control***).

Accreditation standards such as the American National Standards Institute (ANSI) National Accreditation Board (ANAB) Accreditation Requirements (AR) 3125 standards[423] and the FBI

[423] ANSI National Accreditation Board (ANAB). *AR 3125: Accreditation Requirements for Forensic Testing and Calibration (2023)*. 2023. https://anab.qualtraxcloud.com/ShowDocument.aspx?ID=12371. *See* 6.2.3.2.

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QAS [424] require testimony monitoring. The FBI QAS requires that each testifying analyst's testimony is reviewed annually, but it does not specify who should conduct this monitoring.[425] The AR 3125 requirements state that the individual who performs testimony monitoring shall meet the competency requirements in the discipline as a technical reviewer and requires "the individual performing the technical review to have been competency tested to perform [the testing work] that is being reviewed."[426]

It is imperative for testimony monitoring to identify discrepancies in the communication of the results, opinions, and interpretations, and provide a course of action to address any deficiencies or necessary corrective actions. To accomplish this, personnel performing testimony monitoring should have sufficient expertise to identify these deficiencies as well as when the analyst goes outside of their expertise or the limitations of the science.

The Department of Justice's (DOJ's) Office of Legal Policy describes testimony monitoring as "a quality assurance mechanism to ensure testimony is consistent with mandatory laboratory policies and procedures, properly qualified and appropriately communicated."[427] The DOJ has developed Uniform Language for Testimony and Reports (ULTR)[428] guidance documents that govern the testimony and reports of the DOJ's forensic experts. Additionally, the DOJ developed a Testimony Monitoring Framework that applies to all DOJ FSSPs and describes the requirements for testimony evaluation as:[429]

1. *The examiner's testimony was consistent with mandatory component policies and procedures regarding the forensic analysis and interpretation of evidence.*
2. *The examiner's testimonial opinions, conclusions, and statements regarding case-specific facts or data were properly qualified and did not exceed the limitations of any relevant method or discipline.*
3. *The examiner's testimonial conclusions conformed to the requirements of any applicable ULTR document.*

In addition to these evaluation requirements, the DOJ Testimony Monitoring Framework establishes the expectation that a transcript be requested after any testimony that is not directly

[424] Federal Bureau of Investigation (FBI). *Quality Assurance Standards for Forensic DNA Testing Laboratories*. 2020. https://le.fbi.gov/file-repository/forensic-qas-070120.pdf/view.

[425] Ibid. Standard 16.2.

[426] ANSI National Accreditation Board (ANAB). *AR 3125: Accreditation Requirements for Forensic Testing and Calibration (2023)*. 2023. https://anab.qualtraxcloud.com/ShowDocument.aspx?ID=12371. *See* 7.7.1.I.

[427] Office of Legal Policy. Forensic Science. Accessed March 27, 2024. https://www.justice.gov/olp/forensic-science.

[428] United States Department of Justice. *Uniform Language for Testimony and Reports for Forensic Autosomal DNA Examinations Using Probabilistic Genotyping Systems*. 2022. https://www.justice.gov/olp/page/file/1095961/dl.

[429] United States Department of Justice. *Testimony Monitoring Framework*. 2020. https://www.justice.gov/media/1083376/dl.

observed. The DOJ framework also describes the actions that an evaluating official must take if they determine that there was a substantive failure by the examiner.[430]

Approaches to testimony monitoring differ between FSSPs in both how the reviews are conducted and the frequency of reviews. Direct observation and transcript reviews have different benefits and limitations, but both are important to accurately assess expert testimonies. Direct observation provides information that cannot be gleaned from the cold record (e.g., inflection, delivery, demeanor, and the overall effectiveness of the witness in real time). Transcript reviews allow the reviewer to more closely evaluate the accuracy of complex statements and identify errors that might be harder to detect when listening to live testimony. Relying on only one monitoring process, however, does not paint a full picture of the effectiveness of the expert witness.

Both approaches also involve expending resources—monetary as well as time and effort. In-person observations can involve the cost of travel and time away from the FSSP. Transcripts are often costly to acquire and take effort to appropriately review. While the minimum frequency required by the FBI QAS is annual monitoring, it is arguable that testimony should be subjected to more frequent oversight and that infrequent observations deprive experts of the opportunity for feedback.

There are additional human factors considerations with testimony monitoring, as the impact of monitoring on performance has not been studied. Does knowing whether your testimony will be evaluated impact performance? Does having a peer or supervisor present during the testimony improve or inhibit performance? What is the efficacy of an internal peer review over an external review? Is there more potential to identify systemic errors in testimony through external reviews or internal reviews?

Accrediting bodies and professional membership organizations have codes of ethics regarding testimony; however, their ability to oversee, manage reports of misconduct, and enforce consistent quality is limited. As an example, in the Netherlands, the Ministry of Justice and Security has tasked the Netherlands Register of Court Experts with promoting consistent quality among experts involved in the legal process through provisions such as a code of conduct and establishing a mechanism to strike experts from the register after misconduct.[431]

Regardless of the presence of an oversight body providing standardization, FSSPs should consistently update guidance on what their experts should or should not say in court. FSSPs can

[430] Ibid.

[431] In the Netherlands, there are three fields of DNA analysis in which analysts can be recognized as experts: DNA source-level, kinship cases (inference of a level of relatedness), and DNA activity-level where questions regard the activity (i.e., how or when the DNA got there).

communicate this guidance in the form of standard operating procedures (SOPs) or quality guidelines and training.

Clear procedures or guidelines that establish the standardized criteria for the proper performance and review of testimony are essential to ensuring thorough communication and continual improvement of expressing DNA results. **Callout Box 6.4** presents the elements this EWG believes are foundations of an effective testimony monitoring program and human factors to consider when developing a testimony monitoring program.

Callout Box 6.4: Elements of an Effective Testimony Monitoring Program and Human Factors to Consider

The following elements are informed by the FBI[432] and Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF)[433] quality manuals, which are based upon the DOJ Testimony Monitoring Framework.[434]

- Define who requires monitoring.
  - Should all testifying personnel be monitored or only those who provide interpretations and opinions regarding DNA results?
- Define how frequently monitoring will occur.
  - The FBI QAS requires testimony monitoring to be completed on an annual basis.[435]
  - Should the frequency be adjusted for newer analysts or if testimony occurs less frequently?
- Define how monitoring will be conducted.
  - Direct observation or transcript review?
- Have procedures for how the FSSP will ensure monitoring is done.
  - Who is responsible for requesting a transcript or scheduling someone to observe in person?
- Define who is authorized to perform the monitoring.
  - When used as the technical review of testimony, authorized monitors should have been previously competency tested in the discipline they are evaluating.[436]
- Define the assessment criteria to be used for monitoring.
  - For example, requirements for compliance or what constitutes a substantive failure.
- Provide an opportunity for expert witness input prior to the completion of the evaluation.
  - For example, if the expert witness identifies a possible transcription error that impacts the substance of their testimony.
- Define the records that will be used (i.e., forms) and retained.

[432] Federal Bureau of Investigation (FBI). *Quality Assurance Standards for Forensic DNA Testing Laboratories*. 2020. https://le.fbi.gov/file-repository/forensic-qas-070120.pdf/view.

[433] Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF). Laboratory Services Quality Documents. Accessed March 26, 2024. https://www.atf.gov/file/164071/download.

[434] United States Department of Justice. *Testimony Monitoring Framework*. 2020. https://www.justice.gov/media/1083376/dl.

[435] Federal Bureau of Investigation (FBI). *Quality Assurance Standards for Forensic DNA Testing Laboratories*. 2020. https://le.fbi.gov/file-repository/forensic-qas-070120.pdf/view. *See* 16.2.

[436] ANSI National Accreditation Board (ANAB). *AR 3125: Accreditation Requirements for Forensic Testing and Calibration (2023)*. 2023. https://anab.qualtraxcloud.com/ShowDocument.aspx?ID=12371. *See* 7.7.1.1, 6.2.3.2, and 6.2.3.1.

- Define an expectation for turnaround time with the goal of reducing the perpetuation of negative behaviors.
- Define what action(s) to take in the event of a substantive failure or any other identified nonconformances.
  - For example, disclosure of the statement to the sponsoring attorney or initiation of an internal corrective action plan.
- Require that the expert witness receive feedback on their testimony.
  - The expert witness's FSSP management should be involved or made aware of feedback provided from the monitoring.

6.13.1 When Nonconformities Occur

Errors or verbal miscommunications during trial are inevitable. This is true regardless of an expert's experience, expertise, or training and are often the result of other human factors, such as stress, anticipation, and fatigue that can accompany testimony. Other misstatements and transpositions (e.g., a response such as "Yes, that basically means it is the POI's DNA") may occur more easily when the expert has been testifying for a significant period, when the questions have become redundant or hostile, or when the questions posed are inaccurately or unclearly phrased.

The expert must remain diligent throughout the testimony process regardless of these factors and which side is asking the questions. When misstatements are made, there is an ethical obligation on the part of the expert to rectify the misstatement and document the actions taken (see ***Sec. 2.6*: The Duty to Correct or Report Errors and Adverse Events**).[437]

[437] American Board of Criminalistics. *ABC Rules of Professional Conduct*. 2016. https://www.criminalistics.com/uploads/3/2/3/3/32334973/09-0001f_v1.0.1_abc_rules_of_professional_conduct.pdf.

7. How and When Questions in DNA Analysis

7.1 Introduction and Scope

Previous chapters have focused on DNA interpretation to help determine who might be the source of evidence recovered from a crime scene or individual. But a further important question is what activities led to the presence of that DNA. With the increased sensitivity of DNA techniques and sophisticated software, a DNA profile may be developed even when the contributor of that DNA never touched the item or area that was swabbed.[438] Alternatively, a person's DNA may be present when they were not involved in the crime. Therefore, considering *how* or *when* the DNA may have been deposited (or why it was not recovered) can be vital.

Evaluating DNA results given how and when questions is distinct from evaluating results given who question(s). The different evaluations require different methodologies, experience, data, and contextual case information. It is critical that DNA analysts, criminal justice partners, and factfinders are aware of these differences. Otherwise, there is a danger that a factfinder or end-user will infer that an evaluative statement from a DNA comparison answers the questions of how or when the DNA was deposited. This chapter aims to elucidate some of these differences and provide a path towards improving current practice and minimizing the potential for miscarriages of justice.

The Expert Working Group (EWG) is aware of efforts to address these issues occurring outside the United States, but unless otherwise specified, the discussion in this chapter applies to practices occurring within the United States.

7.2 Applying Knowledge about DNA Transfer in Criminal Cases

DNA transfer is the physical movement of DNA from one surface or location to another. The deposition may be through *direct transfer*, as when a hand grasping an object deposits biological material directly on the surface. Alternatively, *indirect* transfer can occur when DNA moves between people or objects via one or more intermediary surfaces, without direct contact between the depositing and receiving surfaces.[439] Except in ground-truth-known experiments, where an individual is observed to have been in contact with a surface/location, it is not possible to know whether the transfer was direct or indirect.

[438] Meakin G, Jamieson A. DNA Transfer: Review and Implications for Casework. *Forensic Science International: Genetics*. 2013; 7(4):434-43. doi:10.1016/j.fsigen.2013.03.013; van Oorschot RAH, Meakin GE, Kokshoorn B, Goray M, Szkuta B. DNA Transfer in Forensic Science: Recent Progress Towards Meeting Challenges. *Genes (Basel)*. 2021; 12(11):1766. doi:10.3390/genes12111766; van Oorschot RAH, Szkuta B, Meakin GE, Kokshoorn B, Goray M. DNA Transfer in Forensic Science: A Review. *Forensic Science International: Genetics*. 2019; 38:140-66. doi:10.1016/j.fsigen.2018.10.014.

[439] van Oorschot RAH, Meakin GE, Kokshoorn B, Goray M, Szkuta B. DNA Transfer in Forensic Science: Recent Progress Towards Meeting Challenges. *Genes (Basel)*. 2021; 12(11):1766. doi:10.3390/genes12111766.

Despite this, in the experience of the EWG and other researchers,[440] it is common for analysts to be asked to address questions regarding direct and indirect transfer during investigations, within reports, and during testimony. Providing opinions about the probability or possibility of direct or indirect transfer, and explaining potential reasons for observing (or not observing) biological results are problematic. Experts risk providing erroneous testimony by focusing on the activities rather than the (value of the) results if the proposed activities occurred.[441] This testimony may lead attorneys or factfinders to conflate the value of the DNA comparison with questions regarding activities. As Jackson and Biedermann state:[442]

> So, at the end of the expert's evidence, the factfinder is left with, on the one hand, an impressive big number (the LR) also, on the other hand, a list of possible explanations for the transfer (because of specific activities). How do they decide what the DNA evidence means, and how does the evidence impact their decision?

So, how should an expert answer questions about how or when the DNA was deposited in a scientifically responsible manner when they are only able to perform (sub-)source evaluations? If the DNA expert does not provide guidance, the factfinder may well carry the DNA comparison results over to issues regarding activities. However, this danger does not mean that an expert is justified in providing an opinion, explanation, or speculation on the possibility of any alleged event.[443] Rather, it means that the expert should clearly communicate that the DNA comparison (likelihood ratio [LR] or Random Match Probability [RMP]) is not meaningful when considering the question of how or when the DNA was deposited.[444]

Evaluations considering factors such as transfer, persistence, and background require an evaluation of the biological results given propositions that address not the source of the DNA, but the activities that may have taken place. This in turn requires the use of data, knowledge, and expertise on DNA transfer, persistence, prevalence, and recovery (DNA-TPPR; see **Callout Box 7.1**), rather than knowledge of DNA profile characteristics, probabilistic genotyping software (PGS), and population frequencies. In this regard, DNA-TPPR, and assessments given **activity-**

[440] Yang YJ, Prinz M, McKiernan H, Oldoni F. American Forensic DNA Practitioners' Opinion on Activity Level Evaluative Reporting. *Journal of Forensic Sciences*. 2022; 67(4):1357-69. doi:10.1111/1556-4029.15063.

[441] Evett IW. Avoiding the Transposed Conditional. *Science & Justice*. 1995; 35(2):127-31. doi:10.1016/S1355-0306(95)72645-4; Hicks T, Buckleton J, Castella V, Evett IW, Jackson G. A Logical Framework for Forensic DNA Interpretation. *Genes (Basel)*. 2022; 13(6):957. doi:10.3390/genes13060957.

[442] Jackson G, Biedermann A. "Source" or "Activity" What Is the Level of Issue in a Criminal Trial? *Significance*. 2019; 16(2):36-9. doi:10.1111/j.1740-9713.2019.01253.x.

[443] Evett IW, Jackson G, Lambert JA. More on the Hierarchy of Propositions: Exploring the Distinction between Explanations and Propositions. *Science & Justice*. 2000; 40(1):3-10. doi:10.1016/S1355-0306(00)71926-5.

[444] Gittelson S, Kalafut T, Myers S, Taylor D, Hicks T, Taroni F, Evett IW, Bright JA, Buckleton J. A Practical Guide for the Formulation of Propositions in the Bayesian Approach to DNA Evidence Interpretation in an Adversarial Environment. *Journal of Forensic Sciences*. 2016; 61(1):186-95. doi:10.1111/1556-4029.12907.

level propositions,[445] are a separate skill, distinct from "standard" DNA profiling and interpretation (see ***Sec. 3.2.1*: Case Management** for a discussion on the *hierarchy of propositions*). It may be a function limited to only a portion of DNA analysts with the required expertise. At present, there are not adequate educational opportunities to inform these types of issues within the United States.

Callout Box 7.1: DNA Transfer, Persistence, Prevalence, and Recovery (DNA-TPPR)

DNA-TPPR affect the presence and composition of DNA profiles. Variables that influence DNA *transfer* include the nature of the surfaces (i.e., porous, semi-porous, or non-porous), whether surfaces are wet or dry, and factors contributing to the extent of the contact (e.g., force, duration, and area).

The *persistence* of DNA refers to the retention or loss of DNA from surfaces after deposition. DNA can persist for many years, but it also can be lost quickly, for example, when the objects are regularly used or washed. Persistence is also influenced by substrate type, body fluid type, environmental conditions, and use or contact after the initial DNA deposition. Microbial activity, cleaning, or significant use of items accelerates DNA loss, whereas a lack of contact, an absence of light or moisture, and certain substrates promote DNA retention.

As a result of transfer and persistence, it is common to find DNA on items and surfaces. Background DNA (also called "foreign DNA") denotes DNA from unknown sources and activities.[446] *Prevalent* DNA denotes DNA from known sources and activities that may be expected from specific individuals.[447] For example, it is expected that DNA collected from the steering wheel of a stolen vehicle will be a mixture from the owner(s)/driver(s) of the vehicle and the unknown person who last drove the car.

Factors influencing DNA *recovery* include the method of collection and the efficiency of the extraction technologies.[448] Significant differences in DNA recovery have been observed between different types of swabs[449] and different collection methods (e.g., swab versus tape lift).[450] These differences must be considered when comparing different studies with different collection methods. Likewise, DNA extraction methods differ in their extraction efficiency,[451] and the same extraction method will vary in efficiency from different substrates and body fluids.[452]

[445] Evett IW, Gill PD, Jackson G, Whitaker J, Champod C. Interpreting Small Quantities of DNA: The Hierarchy of Propositions and the Use of Bayesian Networks. *Journal of Forensic Sciences*. 2002; 47(3):520-30. doi:10.1520/jfs15291j; Hicks T, Buckleton J, Castella V, Evett IW, Jackson G. A Logical Framework for Forensic DNA Interpretation. *Genes (Basel)*. 2022; 13(6):957. doi:10.3390/genes13060957.

[446] Gill P, Hicks T, Butler JM, Connolly E, Gusmao L, Kokshoorn B, Morling N, van Oorschot RAH, Parson W, Prinz M, Schneider PM, Sijen T, Taylor D. DNA Commission of the International Society for Forensic Genetics: Assessing the Value of Forensic Biological Evidence - Guidelines Highlighting the Importance of Propositions. Part II: Evaluation of Biological Traces Considering Activity Level Propositions. *Forensic Science International: Genetics*. 2020; 44:102186. doi:10.1016/j.fsigen.2019.102186.

[447] Ibid.

[448] van Oorschot RAH, Ballantyne KN, Mitchell RJ. Forensic Trace DNA: A Review. *Investigative Genetics*. 2010; 1(1):14. doi:10.1186/2041-2223-1-14.

[449] Seiberle I, Währer J, Kron S, Flury K, Girardin M, Schocker A, Schulz I. Collaborative Swab Performance Comparison and the Impact of Sampling Solution Volumes on DNA Recovery. *Forensic Science International: Genetics*. 2022; 59:102716. doi:10.1016/j.fsigen.2022.102716; Verdon TJ, Mitchell RJ, van Oorschot RAH. Swabs as DNA Collection Devices for Sampling Different Biological Materials from Different Substrates. *Journal of Forensic Sciences*. 2014; 59(4):1080-9. doi:10.1111/1556-4029.12427.

[450] Burmuzoska I, Hogg K, Raymond J, Hitchcock C, Meakin GE. Comparison of Operational DNA Recovery Methods: Swabs Versus Tapelifts. *Forensic Science International: Genetics Supplement Series*. 2022; 8:50-2. doi:10.1016/j.fsigss.2022.09.019.

[451] Ip SCY, Lin S-W, Lai K-M. An Evaluation of the Performance of Five Extraction Methods: Chelex® 100, QIAamp® DNA Blood Mini Kit, QIAamp® DNA Investigator Kit, QIAsymphony® DNA Investigator® Kit and DNA IQ. *Science & Justice*. 2015; 55(3):200-8. doi:10.1016/j.scijus.2015.01.005.

[452] Verdon TJ, Mitchell RJ, van Oorschot RA. Evaluating the Efficiency of DNA Extraction Methods from Different Substrates. *Forensic Science International: Genetics Supplement Series*. 2011; 3(1):e93-4. doi:10.1016/j.fsigss.2011.08.046.

> Although more research is needed on specific aspects of DNA-TPPR and the application of these factors within specific case situations, the international forensic community is continually adding to a significant body of empirical data and knowledge regarding the foundational aspects of DNA-TPPR.[453]

7.2.1 What Is Appropriate for DNA Experts to Say Now?

An expert rarely (if ever) has all the information needed to perform a robust, balanced, and transparent evaluation of biological results regarding transfer or specific activities on the witness stand. Moreover, combining the stress of trial with efforts to recall appropriately detailed aspects of DNA-TPPR literature makes it extremely difficult to make judgments about the biological results given the proposed activities. Addressing these situations during trials could result in unreliable evaluations on the stand that were not subjected to technical review. Performing evaluations given activity-level propositions without proper training and competency may also be in violation of accreditation standards or FSSP policies.

The EWG considers the present situation problematic, where analysts are providing answers to activity-level questions during testimony by acknowledging that a particular mode of transfer is possible. Moreover, it would be problematic to give an opinion on the value of their results considering factors such as transfer and background, without having sufficient validated methods, training and education, competency testing, and quality system assurances available.

Solving these problems will take time, investments, and resources. Meanwhile, questions around DNA-TPPR and activities will continue to arise. Experts need options to assist the factfinder and ways to alert the court to the dangers of conflating evaluations given sub-source propositions with evaluations given activity-level propositions. DNA analysts need guidance on how to stay in their lane and avoid exceeding the boundaries of their methods and expertise.

Table 7.1 offers several examples of proposed responses to such inquiries. Any portion or combination of the responses below would be an acceptable way for the expert to relay that they are unable to provide an opinion about how or when the DNA was deposited (or not, in cases of absence) in a case.

[453] Butler JM. Recent Advances in Forensic Biology and Forensic DNA Typing: INTERPOL Review 2019-2022. *Forensic Science International: Synergy*. 2023; 6:100311. doi:10.1016/j.fsisyn.2022.100311; Butler JM, Willis S. Interpol Review of Forensic Biology and Forensic DNA Typing 2016-2019. *Forensic Science International: Synergy*. 2020; 2:352-67. doi:10.1016/j.fsisyn.2019.12.002; Cadola L, Charest M, Lavallée C, Crispino F. The Occurrence and Genesis of Transfer Traces in Forensic Science: A Structured Knowledge Database. *Canadian Society of Forensic Science Journal*. 2021; 54(2):86-100. doi:10.1080/00085030.2021.1890941; Gosch A, Courts C. On DNA Transfer: The Lack and Difficulty of Systematic Research and How to Do It Better. *Forensic Science International: Genetics*. 2019; 40:24-36. doi:10.1016/j.fsigen.2019.01.012; Meakin G, Jamieson A. DNA Transfer: Review and Implications for Casework. *Forensic Science International: Genetics*. 2013; 7(4):434-43. doi:10.1016/j.fsigen.2013.03.013; van Oorschot RAH, Meakin GE, Kokshoorn B, Goray M, Szkuta B. DNA Transfer in Forensic Science: Recent Progress Towards Meeting Challenges. *Genes (Basel)*. 2021; 12(11):1766. doi:10.3390/genes12111766; van Oorschot RAH, Szkuta B, Meakin GE, Kokshoorn B, Goray M. DNA Transfer in Forensic Science: A Review. *Forensic Science International: Genetics*. 2019; 38:140-66. doi:10.1016/j.fsigen.2018.10.014.

Table 7.1: Proposed responses to questions about how or when the DNA was deposited

Example of Questions Posed to DNA Experts	Proposed Ways for the Expert to Respond
In your opinion, is direct transfer more likely than indirect?	• DNA analysis does not allow a scientist to directly answer how the DNA was deposited (direct or indirect transfer). The DNA results presented in my report regard the comparison of DNA profiles and can only help answer questions about whose DNA may be present or not. • My testimony about the value of the DNA comparison is only meaningful to help the jury determine who the source of the DNA was. That testimony does not provide any information that addresses the issues of how or when.
Could this [alleged activity] have happened?	• Offering an opinion on this question would amount to speculating on what is alleged. It is not my role as a scientist to speculate about or determine what happened.
Is it possible that the DNA was deposited when the Person of Interest (POI) [engaged in an activity at the scene prior to or after the alleged event]?	• It is not my role to discuss the possibility of the alleged event (or any other event). My expertise is based upon DNA profile comparisons which can only assist in helping you answer questions about whose DNA is present or not. • Agreeing that something is "possible" is not the same as offering an opinion about the probability of the results in the context of case-specific circumstances. • Discussing whether something is possible does not help me convey the significance of the results in the context of this case. For example, getting struck by lightning or flipping a coin and getting "heads" are both possible but have very different probabilities.
Are there other explanations for the presence (or absence) of this DNA?	• It would be inappropriate and speculative for me to discuss why the DNA was or was not detected. • Answering this question would not allow me to convey a balanced assessment of the findings in the context of this case. • The only way I can evaluate the results is by considering at least two opposing views.

Forensic science service providers (FSSPs) should provide their DNA analysts with training and guidance, in accordance with other professional guidelines (e.g., the International Society for Forensic Genetics [ISFG])[454] detailing how DNA analysts should respond when confronted with general or case-specific "how" or "when" questions during testimony. For example, guidelines could include that:

- DNA analysts should not opine about how likely, possible, or probable a particular transfer scenario is (e.g., indirect or direct transfer). This is an opinion on the proposition itself which is not the role of the expert.

[454] Gill P, Hicks T, Butler JM, Connolly E, Gusmao L, Kokshoorn B, Morling N, van Oorschot RAH, Parson W, Prinz M, Schneider PM, Sijen T, Taylor D. DNA Commission of the International Society for Forensic Genetics: Assessing the Value of Forensic Biological Evidence - Guidelines Highlighting the Importance of Propositions. Part II: Evaluation of Biological Traces Considering Activity Level Propositions. *Forensic Science International: Genetics*. 2020; 44:102186. doi:10.1016/j.fsigen.2019.102186.

- Reporting that the DNA is consistent with a particular activity is unbalanced. The DNA results could also be consistent with the alternative activity. What should be conveyed to the factfinder is the value of the results.
- DNA analysts should not perform qualitative or quantitative evaluations of their DNA results considering DNA-TPPR for the first time on the witness stand.

Recommendation 7.1: DNA analysts should not opine about the possibility or probability of direct or indirect transfer having occurred in a case.*

*See footnote[455] for dissent statement.

Recommendation 7.2: The evaluation of DNA results given "how" and "when" questions is distinct from the evaluation of DNA results given "who" questions. In order to develop policies and practices on how DNA analysts should respond appropriately to questions about how and when DNA was deposited in a particular case, forensic science service providers should consult professional guidance documents and experts who understand issues related to transfer and persistence. These policies and practices should require DNA analysts to be appropriately trained to respond to such questions.*

*See footnote[456] for dissent statement.

Callout Box 7.2 provides examples of very limited circumstances in which a DNA expert may be able to provide a case-specific opinion on the DNA results given alleged activities. These examples come with a caveat that different analysts and different FSSPs may vary in what they consider "obvious" amounts of material or data to inform such opinions. Future research in this area should contribute knowledge to sources of variability in opinions related to how and when the DNA was deposited, and the types of evaluations that pose the most risk of being inappropriate or dangerous.

[455] Two members (Lynn Garcia and Dawn Boswell) do not support Recommendation 7.1. While they acknowledge that analysts are often asked to respond to "how" and "when" questions in criminal cases and agree that testimony on this subject can be misleading or otherwise problematic, they believe that the broad prohibition in Recommendation 7.1 puts the proverbial "cart before the horse" by not first requiring an assessment of the type outlined in Recommendation 7.3. Moreover, they worry that supporting 7.1 would imply the need for analysts to shift to a new paradigm that has not yet been sufficiently vetted within the specific context of the U.S. court system.

[456] Two members (Lynn Garcia and Dawn Boswell) do not support Recommendation 7.2, not because training on this subject is not important or necessary, but because they question how FSSPs will determine who the "experts" are (for TPPR and formal activity evaluation training) as well as what constitutes "appropriate professional guidance" in the United States. They are also concerned that currently available guidance might not employ the necessary safeguards that typically exist in a quality system of an accredited FSSP (e.g., validation, competency and proficiency testing, appropriate discovery, reporting processes, and similar measures). Additionally, as stated in their objection to 7.1, these members believe Recommendation 7.2 is premature until Recommendation 7.3 is implemented.

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Callout Box 7.2: Limited Circumstances Where a DNA Expert Can Provide Case-Specific Guidance

There may be very limited circumstances in which an expert may be able to use their DNA-TPPR expertise to assist in answering questions about how or when DNA was—or was not—deposited on an item or person. To be acceptable, statements given by the expert would need to focus on the probability of the results given the alleged activities (i.e., the statement must not transpose the conditional). This type of evaluation necessitates time and access to data, and must be peer reviewed. Analyses should not be performed on the stand for the first time.

The limited circumstances include when the amount of material is so large or obvious that it could not be present as background or because of contamination. For example, "The DNA results [observation of multiple sperm heads in all three internal vaginal swabs, single DNA profile after differential extraction compatible with Mr. POI] are more likely to be observed if there was sexual intercourse rather than social interactions only."

Or, if based on the case information available to them, the DNA expert is of the opinion that the DNA results considering the alleged activities are uninformative. For example, "The DNA results [observation of a mixed DNA profile compatible with Mr. POI on the exterior of the underwear] are just as likely to be observed if the POI undressed Ms. A than if they only cohabitated."

7.3 Creating a Path Forward to Improve Current Practice in the United States

The EWG strongly believes that analysts should not provide opinions on direct or indirect transfer. DNA analysts should also not provide opinions on case-specific questions about DNA-TPPR, or the probability of DNA results given activity-level propositions without validated methods, appropriate education, training and competency testing, and suitable quality assurance/quality control (QA/QC) measures in place. In current practice, however, DNA analysts in the United States are being asked questions during testimony that they simply have not been fairly equipped to answer. The following steps provide a starting point to move the DNA community out of this dangerous practice. These steps are not intended to be exhaustive and will require substantial engagement and collaboration at multiple levels—within and between FSSPs, criminal justice partners, researchers, educators, and accrediting bodies.

7.3.1 Provide Education

There is a critical and pressing need to educate FSSPs and DNA analysts about DNA-TPPR issues so that all parties recognize when they may be straying outside their lane of expertise—both scientifically and professionally. This includes an appreciation of:

- The complexity of the subject
- The necessity to be aware of the principles of interpretation
- The differences between providing opinions on the propositions or on the results given the propositions
- Why explanations may not be helpful during testimony

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- The potential for miscarriages of justice to occur due to incorrect or inappropriate testimony

Of equal importance is educating criminal justice partners on DNA-TPPR and why current DNA profiling methods and interpretations are not able to address activity-level propositions. This education should be aimed toward ensuring that expert reports and testimony are not misunderstood or misused. Until there is a shared understanding, DNA analysts are acting as their own gatekeeper, as courts may not realize when an expert is providing an opinion on an issue that is beyond their expertise or that cannot be addressed by the biological results.

7.3.2 Review International Experience

Internationally, there are methods and guidelines in use for the interpretation and reporting of biological results given activity-level propositions.[457] These methods have been implemented within both inquisitorial and adversarial legal systems and follow the principles of evaluative reporting as described for reporting DNA results when the issue is the source of the DNA (see ***Sec. 3.5: Comparison Phase***). International experience and forensic science implementation norms require analyst education, training, and competency testing against a validated method, and only allow performance of these evaluations under a logical framework that provides for the proper interpretation, reporting, and testimony of these opinions.[458]

Understanding how international FSSPs have developed and implemented these methods, on which type of cases, and how education and engagement with criminal justice partners has evolved could provide valuable insights for how the United States can move forward.[459] The DNA community must also consider the different legal constraints, resourcing issues, and educational challenges specific to the United States when seeking guidance and potential solutions from international experience.

7.3.3 Invest in DNA-TPPR Research and Application of Research

The high sensitivity of the chemistry used in the forensic DNA laboratories today enables FSSPs to obtain DNA profiles with less DNA. This produces more investigative leads but comes with the

[457] Kokshoorn B, Luijsterburg M. Reporting on Forensic Biology Findings Given Activity Level Issues in the Netherlands. *Forensic Science International*. 2023; 343:111545. doi:10.1016/j.forsciint.2022.111545; Taylor D, Kokshoorn B. *Forensic DNA Trace Evidence Interpretation: Activity Level Propositions and Likelihood Ratios*. CRC Press: Boca Raton, 2023. doi:10.4324/9781003273189; Taylor D, Kokshoorn B, Biedermann A. Evaluation of Forensic Genetics Findings Given Activity Level Propositions: A Review. *Forensic Science International: Genetics*. 2018; 36:34-49. doi:10.1016/j.fsigen.2018.06.001.

[458] Gill P, Hicks T, Butler JM, Connolly E, Gusmao L, Kokshoorn B, Morling N, van Oorschot RAH, Parson W, Prinz M, Schneider PM, Sijen T, Taylor D. DNA Commission of the International Society for Forensic Genetics: Assessing the Value of Forensic Biological Evidence - Guidelines Highlighting the Importance of Propositions. Part II: Evaluation of Biological Traces Considering Activity Level Propositions. *Forensic Science International: Genetics*. 2020; 44:102186. doi:10.1016/j.fsigen.2019.102186.

[459] Kokshoorn B, Luijsterburg M. Reporting on Forensic Biology Findings Given Activity Level Issues in the Netherlands. *Forensic Science International*. 2023; 343:111545. doi:10.1016/j.forsciint.2022.111545; Taylor D, Kokshoorn B. *Forensic DNA Trace Evidence Interpretation: Activity Level Propositions and Likelihood Ratios*. CRC Press: Boca Raton, 2023. doi:10.4324/9781003273189.

challenges associated with any transfer evidence (e.g., fibers, gunshot residues, or drugs). Although there is an existing body of literature on the impact of different variables and conditions on DNA-TPPR, there is a need for data assessing the value of biological results considering activities that are encountered in casework, with techniques used by FSSPs.

Given the number of variables that could impact the value of the findings, international harmonization, standardization, and collaboration of experimental design and data sharing is required.[460] Although there are databases[461] to collate, search, and assist in finding relevant research given specific parameters, there is a need for greater standardization, maintenance, support, and resourcing for these efforts. Targeting research at relevant and realistic scenarios is required, so that FSSPs build a greater body of empirical data both for expanding their knowledge and acquiring data on which to base robust evaluations. Similar initiatives are taking place in Europe.[462]

There is also a need to provide education and training for DNA analysts on how to use and apply DNA-TPPR data and published research. Not all research is equal in quality or is appropriate to use in all situations and circumstances. Those applying the research need an in-depth and critical understanding of interpretation, research design principles, limitations, assumptions, and dependencies to ensure that empirical data is used appropriately to guide and inform evaluations given activity-level propositions. The importance of research culture to improve knowledge is discussed in ***Sec. 12.2*: Research Culture.**

7.3.4 Understand and Evaluate Risks of Bias, Variability, and Error

Researchers should also evaluate, and develop ways to mitigate, the human factors impact of performing evaluations given activity-level propositions. The development of case-specific propositions addressing the relevant issues requires knowledge of additional case information, some of which may promote unconscious bias. Due to the complexity of evaluations given activity-level propositions, and the number and nature of variables that may need to be considered, there is also a likelihood of inter- and intra-examiner variability in the choice of propositions, the selection of studies to inform probabilities, the evaluation of the studies, and the value of the DNA findings given the propositions. Research is required to evaluate the magnitude of this variability, and to develop strategies to minimize it where possible to reduce potential error.

[460] Taylor D, Kokshoorn B, Biedermann A. Evaluation of Forensic Genetics Findings Given Activity Level Propositions: A Review. *Forensic Science International: Genetics*. 2018; 36:34-49. doi:10.1016/j.fsigen.2018.06.001.

[461] DNA-TrAC. Keeping Track of DNA Transfer. Accessed Feb 10, 2024. https://www.dropbox.com/sh/jf286hcollyerlf/AABQHfhGGiB03YdcJgpO4NUga?+dl=0.

[462] For example, the establishment of a Trace DNA Transfer Rate Repository & Bayes Net to Calculate LRs (Understanding the transfer of DNA), https://enfsi.eu/projects/monopoly-programmes-mp/mp2020/).

7.3.5 Assess Feasibility to Validate and Implement Methods

Forensic science methods must be shown to be reliable, reproducible, and accurate, both at a foundational level and within each individual laboratory.[463] Evaluations given activity-level propositions are no different. Prior to implementation within an FSSP, internal validation studies must be performed to demonstrate that the established method and the trained analysts are able to produce reliable results. In addition, the results must be reported in a transparent and appropriate manner. Such validation studies should demonstrate the ability for the methodology to provide evaluations supporting ground truth, the variability that may arise from different applications of the method, and the limitations and restrictions that analysts must be aware of.

Similarly, implementation post-validation requires appropriate training for all analysts using the method, competency testing, relevant ongoing proficiency testing, auditing, testimony monitoring, and the development of standard operating procedures (SOPs) and reporting procedures. Critically, it is also vital that FSSPs engage and educate criminal justice partners *prior* to the implementation of reporting findings given activity-level propositions, to ensure that end-users and factfinders are aware of how and when these evaluations can be performed, when they cannot be, and how the opinions should or should not be used.

7.3.6 Summary

Beyond the recommendations in this chapter, significant work is required to provide the United States DNA community with best practice recommendations for evaluations of biological results given activity-level propositions. The current state of practice on this subject could lead to miscarriages of justice, and the EWG agrees that it is a matter of urgency to provide DNA analysts and other criminal justice partners with the educational opportunities the enable a better understanding of how and why the current practice is problematic. Efforts to improve the DNA community's current understanding and application of knowledge should be collaborative, to include DNA analysts, FSSPs, criminal justice partners, legal practitioners, and cognitive scientists (see ***Sec. 12.3*: Opportunities for Expanding and Improving the Research Culture in Forensic DNA Analysis**).

[463] President's Council of Advisors on Science and Technology (PCAST). *Report to the President: Forensic Science in Criminal Courts: Ensuring Scientific Validity of Feature-Comparison Methods*. 2016. https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/PCAST/pcast_forensic_science_report_final.pdf.

Recommendation 7.3: The federal government should fund collaborative efforts to review the foundations and principles of evaluating biological results when considering alleged activities. Based on the findings, additional fiscal support should be available to educate and guide DNA and legal communities on the review, research, selection, and validation of appropriate methods to account for DNA transfer, persistence, prevalence, and recovery when assessing biological results.

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8. Quality Assurance/Quality Control

8.1 Introduction and Scope

Forensic science service providers (FSSPs) use quality assurance (QA) and quality control (QC) systems to produce reliable and accurate results. QA focuses on preventing errors through policies, procedures, validations, and documentation, whereas QC focuses on detecting errors. A successful QA/QC system should promote accuracy and minimize error by creating and promoting a work environment where DNA analysts have the support and resources to meet required standards and produce high-quality work.

The 2009 National Academy of Sciences Report broadly recommended that:[464]

> Forensic laboratories should establish routine QA and QC procedures to ensure the accuracy of forensic analyses and the work of forensic practitioners. QC procedures should be designed to identify mistakes, fraud, and bias; confirm the continued validity and reliability of standard operating procedures and protocols; and correct procedures and protocols that are found to need improvement.

To meet this recommendation, a QA/QC system incorporating effective management, documentation, and practitioner education is required. Many FSSPs use accreditation to ensure their QA/QC programs are performing appropriately and that the work processes governed by the system comply with standards developed or set by bodies such as ASTM[465] and the International Organization for Standardization/International Electrotechnical Commission (ISO/IEC).[466]

Although these standards set minimum requirements that FSSPs should adhere to, they often do not address human factors issues that can occur within workflows. This chapter describes critical aspects of QA/QC systems that FSSPs should incorporate as part of a high-functioning quality system, and the human factors that can impact the effectiveness of that system.

8.2 Quality Management Systems

A quality management system (QMS) is "a formalized system that documents processes, procedures, and responsibilities for achieving quality policies and objectives. A QMS helps coordinate and direct an organization's activities to meet customer and regulatory requirements

[464] National Research Council, Committee on Identifying the Needs of the Forensic Science Community. *Strengthening Forensic Science in the United States: A Path Forward*. The National Academies Press: Washington, DC, 2009. doi:10.21428/cb6ab371.b2d683d2.

[465] ASTM International. Homepage. Accessed March 23, 2024. https://www.astm.org/.

[466] International Organization for Standardization (ISO). International Electrotechnical Commission. Accessed March 27, 2024. https://www.iso.org/organization/70.html.

and improve its effectiveness and efficiency on a continuous basis."[467] In an FSSP, the QMS contains administrative and technical policies, procedures, and supporting documents for FSSP management and personnel to use to consistently produce high-quality, technically supported results and conclusions.

8.2.1 Policies and Procedures

Policies and procedures aim to ensure a consistent application of quality and technical processes; therefore, technical procedures within the QMS should focus on detailing the steps necessary for consistent performance of validated techniques and methods. Procedures should be written to ensure an analyst who has demonstrated competency can replicate the steps the same way each time they complete the relevant process.

An FSSP's policies and procedures should be primarily data driven. For example, recording and evaluating nonconformities, corrective actions (see ***Sec. 8.10.2: Corrective Actions***), and proficiency test results allows useful data to be generated and helps identify opportunities for ongoing improvement. Using these data, an FSSP can respond to issues that arise, quantify/qualify these issues, and measure or gauge improvement.

In addition to well-written technical procedures, FSSP policies and procedures should address guidance and approaches for reducing cognitive bias during processing and interpretation such as using controls (see ***Sec. 8.3.5: Quality Control***) and managing contextual information (see ***Sec. 3.3.4: Contextual Information Management***).

Most FSSP technical procedures are developed through internal validation, which includes optimizing or testing a method to arrive at a standard operating procedure (SOP). SOPs delineate step-by-step instructions to successfully complete a process or task. By capturing requirements and necessary steps in SOPs, FSSP personnel have a consistent point of reference to ensure appropriate performance of a validated procedure. FSSPs can also use tools (e.g., user guides, work instructions, forms, checklists) to help perform a documented procedure appropriately.

To be useful and effective, procedures in a QMS should be evaluated and improved when needed. FSSPs can initiate improvements because of a corrective action (see ***Sec. 8.10.2: Corrective Actions***) or a preventive action, or simply because they have identified an opportunity for improvement through research, collaboration, or innovation. This continuous improvement

[467] American Society for Quality. What Is a Quality Management System (QMS)? Accessed March 23, 2024. https://asq.org/quality-resources/quality-management-system.

This publication is available free of charge from: https://doi.org/10.6028/NIST.IR.8503

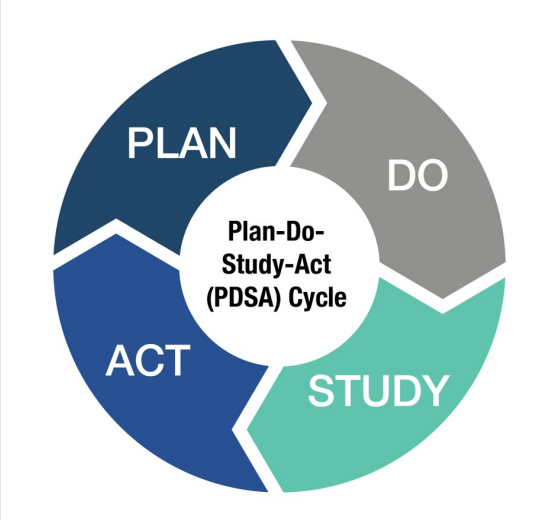
process is often referred to as Deming's cycle or the Plan-Do-Study-Act (PDSA) cycle as described in **Callout Box 8.1**.[468]

SOPs may not reduce errors if FSSP personnel cannot easily and accurately understand them or fail to follow them. FSSPs should write SOPs clearly and concisely to make them easy for trained analysts to use and should format them so that the required steps are readily apparent.[469] Overly dense paragraphs of information can be difficult to follow when performing tasks in the laboratory, whereas bullet points can help focus a reader's attention and serve as a checklist.[470]

Information needed to complete a task that is dispersed in multiple procedures or in different sections of one procedure may be difficult for the analyst to locate. All information relevant to a procedure should be presented in a centralized and easily locatable place. Analysts are also obligated to seek clarity if they are having difficulty understanding an SOP. FSSP management should encourage feedback and suggestions for improvement from personnel.

Callout Box 8.1: PDSA Cycle

The PDSA cycle is a systematic process used for continuous improvement. The four steps provide a framework for developing, testing, and implementing change that allows improvements to be tested on a small scale before wider implementation.



The four steps of the cycle are as follows:

- **Plan:** Define objectives and form hypotheses about what will happen and why. This stage should establish what will be done, who will perform it, where and when it will be performed, and what data will be collected to determine if a tangible improvement has occurred.

[468] Henshall A. How to Use The Deming Cycle for Continuous Quality Improvement. Accessed March 27, 2024. https://www.process.st/deming-cycle/.

[469] FDA Group. A Basic Guide to Writing Effective Standard Operating Procedures (SOPs). Accessed March 27, 2024. https://www.thefdagroup.com/blog/a-basic-guide-to-writing-effective-standard-operating-procedures-sops.

[470] Ibid.

This publication is available free of charge from: https://doi.org/10.6028/NIST.IR.8503

- **Do:** The plan is carried out, observations are documented, and data are collected.
- **Study:** Data are analyzed, and results are compared to predictions. Conclusions should be drawn regarding the effectiveness of the change.
- **Act:** Refinements or modifications may be required to the change based on the data. The change may be implemented or another PDSA cycle may commence.

PDSA cycles may run sequentially or simultaneously, particularly in instances when multiple changes are being trialed. Simultaneous cycles are more commonly used when multiple complex changes are required, including where interactions may occur between the different components involved.

Research conducted in aviation showed that both the volume and number of procedures in use can pose a barrier to implementation.[471] Specifically, "front-line employees tend to ignore, or modify, what they perceive to be over-specified impractical procedures,"[472] and they may find that "the body of procedures regulating an area of work sometimes appear as a 'jungle' of procedures."[473]

The effectiveness of an SOP is therefore a balance between containing enough information to support consistent application among analysts while not overburdening analysts with unnecessary, repetitive, and disorganized information. It may be beneficial to trial SOPs with a range of personnel with multiple skill sets before formal introduction to ensure understanding and ease of use.

Once personnel repeatedly use the same procedure to a point where they can complete a task or process without referring to a written protocol, there is a risk of procedural drift. Procedural drift occurs when the application of a procedure strays from the written instructions.[474] This drift is often a result of small, incremental, and undetected deviations over time that become the norm at an individual or laboratory level (see ***Sec. 10.6.2*: *Peer Pressure***).

Although FSSPs may put QC systems in place (e.g., positive and negative control samples) to detect the success or failure of a process, it is more difficult to embed mechanisms within a procedure to prevent minor deviations that are unlikely to result in a failure or noticeably different output. Consequently, in the absence of proactive QA/QC strategies, these deviations often go undetected.

[471] Johnston N. The Paradox of Rules: Procedural Drift in Commercial Aviation. Proceedings of the Twelfth International Symposium on Aviation Psychology, Dayton, OH, 2003. https://cognitivesystemsdesign.net/Papers/Johnston%20(2003).pdf

[472] Ibid. p. 634.

[473] Antonsen S, Almklov P, Fenstad J. Reducing the Gap between Procedures and Practice - Lessons from a Successful Safety Intervention. *Safety Science Monitor*. 2008; 12(1):1-16. p. 3.

[474] Aerossurance. 'Procedural Drift': Lynx CFIT in Afghanistan. Accessed March 23, 2024. https://aerossurance.com/helicopters/procedural-drift-lynx-cfit/.

This publication is available free of charge from: https://doi.org/10.6028/NIST.IR.8503

Quality activities such as a second analyst observing the actions of the first, annual quality system reviews, and internal or external observational audits can help detect procedural drift, including those errors that may have previously gone unnoticed. Additionally, these activities may identify improvements, or allow analysts to recommend improvements, to existing work processes.

Alternatively, FSSPs can modify work practices to mitigate the potential for procedural drift and minimize error by adding requirements such as checklists, physical cues (e.g., moving a tube once a reagent is added), or engineering controls designed to reduce risk. The use of automation, Laboratory Information Management Systems (LIMS), and other software tools that guide analysts through the steps of a procedure are common engineering controls[475] used to prevent or reduce procedural errors.[476]

8.2.2 Accreditation

Accreditation for FSSPs is, today, a practical necessity to operate. Within the United States, the DNA Identification Act of 1994 required FSSPs to be "accredited by a nonprofit professional association" and to "demonstrate compliance with standards established by the Director of the Federal Bureau of Investigation" to participate in the National DNA Index System (NDIS).[477]

Both major accrediting bodies, ANSI National Accreditation Board (ANAB) and American Association for Laboratory Accreditation (A2LA)[478] require accredited FSSPs to follow ISO/IEC 17025[479] and the Federal Bureau of Investigation's Quality Assurance Standards (FBI QAS)[480] for NDIS access. ANAB further requires compliance with their AR 3125[481] while A2LA requires compliance with ISO/IEC R221.[482]

[475] Ricardo & Barbosa. Using Human Factors, Human Error Prevention, and Mistake Proofing. Accessed March 27, 2024. https://www.ricardo-barbosa.com/using-human-factors-human-error-prevention-and-mistake-proofing/.

[476] InVita Healthcare Technologies. DNA & Forensic Sample Management Solutions. Accessed March 27, 2024. https://www.invitahealth.com/solutions/dna-and-forensics/.

[477] Office of the Law Revision Counsel of the United States House of Representatives. *34 USC 12591: Part A–DNA Identification: Quality Assurance and Proficiency Testing Standards*. 2023. https://uscode.house.gov/view.xhtml?req=granuleid%3AUSC-prelim-title34-chapter121-subchapter8-partA&edition=prelim.

[478] American Association for Laboratory Accreditation (A2LA). Forensic Examination Accreditation Program. Accessed March 23, 2024. https://a2la.org/accreditation/forensics/; ibid.

[479] International Organization for Standardization (ISO). *General Requirements for the Competence of Testing and Calibration Laboratories, ISO/IEC 17025:2017*. 2017. https://www.iso.org/standard/66912.html.

[480] Federal Bureau of Investigation (FBI). *Quality Assurance Standards for Forensic DNA Testing Laboratories*. 2020. https://le.fbi.gov/file-repository/forensic-qas-070120.pdf/view.

[481] ANSI National Accreditation Board (ANAB). *AR 3125: Accreditation Requirements for Forensic Testing and Calibration (2023)*. 2023. https://anab.qualtraxcloud.com/ShowDocument.aspx?ID=12371.

[482] American Association for Laboratory Accreditation (A2LA). Forensic Examination Accreditation Program. Accessed March 23, 2024. https://a2la.org/accreditation/forensics/.

The existing laws expand those requirements for any state or local FSSP to be eligible to receive federal grant funding.[483] Internationally, different governing and regulatory bodies may have different requirements for accreditation, or no formal requirements may exist. However, most countries require accreditation to ISO/IEC 17025 for contribution to national and international databases.

8.2.3 Standards

Although accreditation requires an FSSP to show conformance with designated standards, an FSSP can choose to adhere to standards without accreditation, and an accredited FSSP can choose to follow additional standards not required by an accrediting body. Standards attempt "to capture, evolve, and improve current practice and to draw important lines in the sand as to what is no longer acceptable practice."[484] In addition to standards, FSSPs may choose to adhere to best practice recommendations and guidelines (see ***Sec. 8.2.4*: Guidelines and Best Practice Documents**).

Each FSSP could, in theory, develop their own QMS requirements, but this would entail significant duplication of effort and a potential decrease in accountability without regular oversight of conformance. Additionally, standards development and maintenance are time-consuming processes that require consideration of broadly-based input from interested parties.

In forensic science, interested parties are not only FSSPs. A broader group of professionals involved in the criminal justice system can be useful in creating standards, and standards developers should engage with these criminal justice partners during the development process.[485] Adoption and promotion of regional, national, or international standards to which FSSPs agree to operate under can promote delivery of a consistently high-quality service or product.

The extent to which standards are intended to move a discipline forward or only to prescribe a minimally acceptable level of performance is open to debate. Robertson et al. state that the purpose of standards is not "to meet minimum levels, best practice, or even aspirational levels of practice. The reality is that standards are aimed at acceptable professional practice, otherwise they would have no chance of being consensus documents."[486]

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[483] United States Code Office of the Law Revision Counsel. *34 USC 40701: The Debbie Smith DNA Backlog Grant Program*. 2018. https://uscode.house.gov/view.xhtml?req=42+U.S.C.+%EF%BF%BD+14135&f=treesort&fq=true&num=0&hl=true&edition=prelim&granuleId=USC-prelim-title34-section40701.

[484] Robertson J, Kent K, Wilson-Wilde L. The Development of a Core Forensic Standards Framework for Australia. *Forensic Science Policy & Management: An International Journal*. 2014; 4(3-4):59-67. doi:10.1080/19409044.2013.858797. p. 66.

[485] Ibid.

[486] Ibid. p. 65.

In practice, many FSSPs use standards to define the minimal expectations for a "quality" service. It also seems that standards developing organizations (SDOs) determine a level of acceptable professional practice by striking a balance between the requirements of the industry and criminal justice partners alongside what is achievable based on resources.

Notwithstanding these debates, the general purpose of standards is to ensure products and services are safe, reliable, and meet appropriate professional practices. As science evolves, so should the standards. This evolution introduces human factors with a need to upkeep the standards and maintain compliance with the applicable standards in place at any given time.

Although standards are intended to "enhance the reliability, transparency and confidence in forensic evidence" and "harmonize work practices," [487] there is room for variability in conformance with a standard. Variations in FSSP size and capabilities may require flexibility in the means for effectuating results-based standards for performance.

An FSSP that only conducts DNA testing and has a small number of technical personnel will have different considerations for how to comply with a standard than an FSSP capable of testing in several disciplines with numerous personnel in administrative and technical roles. Although FSSPs may differ in how they implement standards, they should be able to demonstrate adherence to them.

FSSP personnel will also have varying experience with standards development, implementation, and application. An individual who has worked in or with other FSSPs might have exposure to different ways a standard can be met. Additionally, personnel who have received training in auditing or have had an opportunity to participate on an assessment team might have greater familiarity with the applicable standards and be aware of differing effective strategies for compliance with various standards.

Maintaining the relevance of forensic DNA standards is challenging because of the rapid pace of technological advancements. Standards development is a lengthy process that requires involvement from volunteers with various experience in the current and emerging technologies. It can take years before a standard is approved. Then, once a standard is issued, depending upon the content, it should be regularly reviewed and updated to ensure its continued efficacy.[488]

There are several national and international organizations that develop, publish, or maintain standards. Each organization has a different scope and focus, and it is important that FSSPs understand the role of each body within quality management. Depending on the standard,

[487] International Organization for Standardization (ISO). *Forensic Sciences - Part 1: Terms and Definitions, ISO/IEC 21043-1:20018(En)*. 2018. https://www.iso.org/obp/ui/#iso:std:iso:21043:-1:ed-1:v1:en.

[488] Organization of Scientific Area Committees (OSAC). OSAC Registry Approval Process. Accessed March 27, 2024. https://www.nist.gov/organization-scientific-area-committees-forensic-science/registry-approval-process.

adherence may be legislatively required or voluntary. Keeping track of the breadth of requirements and guidance can be difficult and a contributing human factor. The major organizations developing forensic science standards are listed below.

8.2.3.1 International Organization for Standardization

ISO is a nongovernmental organization comprising national standards bodies. It "brings together experts to share knowledge and develop voluntary, consensus-based, market relevant international standards that support innovation and provide solutions to global challenges."[489] ISO and the IEC develop joint ISO/IEC documents such as ISO/IEC 17025.[490] International standards for forensic science (ISO/IEC 21043) are currently in development and are being drafted in separate parts: Part 1, "Terms and Definitions"[491] and Part 2, "Recognition, recording, collecting, transport and storage of material."[492]

A goal of these standards is to "harmonize work practices to facilitate forensic facilities from different countries to work collaboratively in response to cross-border investigations."[493] By developing international forensic standards, facilities from different countries could then "support one another in the event of a catastrophic event that exhausts a country's capabilities."[494]

8.2.3.2 Standards Australia

The ISO/IEC 21043 standard resembles, in part, the Australian standards developed by the National Institute of Forensic Science, a directorate within the Australian and New Zealand Policing Advisory Agency (ANZPAA NIFS), and Standards Australia. AS 5388[495] was developed as a core non–discipline-specific standard in four parts for the forensic process from crime scene to reporting.[496] It was envisioned that discipline-specific standards could supplement this base support structure.[497] AS 5388 was the first standard of its type and has since become a

[489] International Organization for Standardization (ISO). About ISO. Accessed March 27, 2024. https://www.iso.org/about-us.html.

[490] International Organization for Standardization (ISO). *General Requirements for the Competence of Testing and Calibration Laboratories, ISO/IEC 17025:2017*. 2017. https://www.iso.org/standard/66912.html.

[491] International Organization for Standardization (ISO). *Forensic Sciences - Part 1: Terms and Definitions, ISO/IEC 21043-1:20018(En)*. 2018. https://www.iso.org/obp/ui/#iso:std:iso:21043:-1:ed-1:v1:en.

[492] International Organization for Standardization (ISO). *Forensic Sciences - Part 2: Recognition, Recording, Collecting, Transport, and Storage of Items, ISO/IEC 21043-2:2018*. 2018. https://www.iso.org/standard/72041.html.

[493] International Organization for Standardization (ISO). *Forensic Sciences - Part 1: Terms and Definitions, ISO/IEC 21043-1:20018(En)*. 2018. https://www.iso.org/obp/ui/#iso:std:iso:21043:-1:ed-1:v1:en.

[494] Ibid.

[495] Standards Australia. *Forensic Analysis Reporting. AS 5388.4-2013* 2013. https://infostore.saiglobal.com/en-us/standards/as-5388-4-2013-120014_saig_as_as_251524/.

[496] Wilson-Wilde LM, Brandi J, Gutowski SJ. The Future of Forensic Science Standards. *Forensic Science International: Genetics Supplement Series*. 2011; 3(1):e333-4. doi:10.1016/j.fsigss.2011.09.029.

[497] Robertson J, Kent K, Wilson-Wilde L. The Development of a Core Forensic Standards Framework for Australia. *Forensic Science Policy & Management: An International Journal*. 2014; 4(3-4):59-67. doi:10.1080/19409044.2013.858797.

foundational platform for the development of the ISO/IEC 21043 standards, albeit with varying levels of adaptation across the component parts for use as international standards.[498]

8.2.3.3 Federal Bureau of Investigation

As described previously, United States FSSPs that participate in NDIS or receive federal funding are required to operate in accordance with the FBI QAS for Forensic DNA Laboratories and DNA Databasing Laboratories. The FBI QAS was originally developed by the federal DNA Advisory Board (DAB) as required by the DNA Identification Act of 1994. When the federal DAB statutory period expired, the Scientific Working Group on DNA Analysis Methods (SWGDAM) was charged with recommending revisions to the FBI for the QAS.[499]

Federal law establishing NDIS requires that FSSPs are externally audited to these standards no less than once every two years.[500] FSSPs that do not participate in NDIS, do not perform testing as a vendor of a NDIS laboratory, or do not wish to be eligible for federal funding have no federally legislated requirement to follow the FBI QAS.

8.2.3.4 Organization of Scientific Area Committees

The National Institute of Standards and Technology (NIST) established the Organization of Scientific Area Committees for Forensic Science (OSAC) in 2014 to address a lack of forensic science standards.[501] Discipline-specific subcommittees draft proposed standards, which, if approved by the subcommittee and the Forensic Science Standards Board, are sent to an SDO for further development (typically ASTM International and the American Academy of Forensic Sciences [AAFS] Standards Board [ASB]) and published on the OSAC Registry.

OSAC members can also work directly on standards initiated within an SDO. Standards not developed by OSAC can appear on the OSAC Registry at the request of an OSAC unit. Because of SWGDAM's role in informing the FBI QAS, SWGDAM's responsibilities were not fully migrated to the OSAC structure as was true in other disciplines, and SWGDAM continues to operate parallel to the work of OSAC.[502]

There is no legal requirement for FSSPs to implement OSAC standards. However, individual states may have additional oversight commissions or regulations that suggest or require adherence to

[498] Ibid.

[499] Scientific Working Group on DNA Analysis Methods (SWGDAM). About Us. Accessed March 28, 2024. https://www.swgdam.org/about-us.

[500] Office of the Law Revision Counsel of the United States House of Representatives. *34 USC 12592: Index to Facilitate Law Enforcement Exchange of DNA Identification Information*. 2023. https://uscode.house.gov/view.xhtml?req=granuleid:USC-prelim-title34-section12592&num=0&edition=prelim#:~:text=34%20USC%2012592%3A%20Index%20to%20facilitate%20law%20enforcement,those%20laws%20in%20effect%20on%20September%2029%2C%202022.

[501] National Institute of Standards and Technology (NIST). The Organization of Scientific Area Committees for Forensic Science. Accessed March 27, 2024. https://www.nist.gov/organization-scientific-area-committees-forensic-science.

[502] Ibid.

published standards. For example, the Texas Forensic Science Commission recommended that FSSPs adopt OSAC Registry standards, but adoption is left to each FSSP.[503] Accredited FSSPs that choose to implement additional standards would subsequently be eligible to be evaluated for conformity during audits (to the extent the standards are appropriate for conformity assessment) and are detailed in the FSSP's QMS.[504]

8.2.4 Guidelines and Best Practice Documents

In addition to standards documents, professional organizations (e.g., SWGDAM, the International Society for Forensic Genetics [ISFG] DNA Commission, and the European Network of Forensic Science Institutes [ENFSI]) and SDOs can develop guidelines or best practice documents that include recommendations for targeted topic areas. Guidelines are often defined as a recommended practice that allows some discretion or leeway in its interpretation, implementation, or use.[505]

These guidelines or best practice documents may provide more specifics regarding an analytical method or examination procedure. For example, where a standard may require the FSSP to have and follow a procedure, a guideline may provide more details on what the procedure should include.

Although guidelines may contain some prescriptive elements and are intended as recommendations or suggested ways of how to comply with formal standards rather than mandatory auditable requirements, organizations such as OSAC have used previous guideline recommendations to draw from and build upon for standards development.[506]

8.2.5 Documentation and Assessment of Compliance

Accrediting bodies require FSSPs to be audited periodically to ensure compliance or conformance with standards and internal policies and procedures. To supply the necessary evidence of compliance, FSSPs should maintain records to support their QMS and technical operations.

Accrediting bodies or other auditing groups use subject matter experts to assess FSSP conformance with standards; even these assessments and audits can be prone to human factors.

[503] National Institute of Standards and Technology (NIST). Houston Forensic Science Center to Voluntarily Adopt OSAC Standards. Accessed March 27, 2024. https://www.nist.gov/news-events/news/2018/12/houston-forensic-science-center-voluntarily-adopt-osac-standards.

[504] Organization of Scientific Area Committees (OSAC). OSAC Registry Implementation: Frequently Asked Questions. Accessed March 27, 2024. https://www.nist.gov/osac/osac-registry-implementation-faqs.

[505] ASTM International. *ASTM E2916-19e1: Standard Terminology for Digital and Multimedia Evidence Examination*. 2019. https://www.astm.org/e2916-19e01.html.

[506] National Institute of Standards and Technology (NIST). Two New Forensic DNA Standards Added to the OSAC Registry. Accessed March 27, 2024. https://www.nist.gov/news-events/news/2020/05/two-new-forensic-dna-standards-added-osac-registry.

With limited time and personnel allocated to review an FSSP's records covering a scope of typically one to four years, auditors often rely on sampling to assess conformance with standards.

Certain terms, when used in standards, require the FSSP to have written objective evidence of compliance. Examples of such terms include "agreed," "appoint," "define," "procedure," and "specify."[507] Written documentation such as policies, procedures, or other records is necessary wherever these terms are used in standards. Proper records reflect compliance with FSSP protocols and are important for transparency in the legal system. FSSPs should generate and maintain records with awareness that these records not only reflect compliance with protocols but also support the validity and reliability of the scientific testing conducted.

A successful audit does not guarantee the validity of all the work being done by the FSSP. Further, quality systems, accreditation, and adherence with standards should not be extrapolated to mean a system is immune from human factors. Indeed, many standards require FSSPs to have mechanisms in place to detect, prevent, and correct errors.

The process for assessing conformance with standards can also be impacted by several human factors. For example, training may ensure an auditor is prepared to assess conformance with the studies required during validation, but it does not necessarily prepare an auditor to review validation data to the extent necessary to determine validity.

Time constraints and auditing team experience may prohibit a deep dive into the supporting data when reviewing validation summaries or unfamiliar technical procedures. Although training to the standards (e.g., FBI QAS) does exist, this training is focused on relaying information about the content of the standards and not necessarily the technical expertise required to review another FSSP's records. To address this, it is important that audit teams are constructed to ensure the auditors' expertise covers the topics that are being assessed.

Auditing teams composed of technical assessors are often employees at other FSSPs who are auditing as volunteers and are balancing time away from their own commitments. These peer auditors may have the appropriate technical knowledge necessary to conduct an audit, but they are also auditing their peers and will not be immune to the human factors impacts of peer assessments.[508]

For example, prior reputation in the community may impact an auditor's preconception of an FSSP and therefore their interpretation of compliance. Likewise, auditors from FSSPs using the

[507] ANSI National Accreditation Board (ANAB). *AR 3125: Accreditation Requirements for Forensic Testing and Calibration (2023)*. 2023. https://anab.qualtraxcloud.com/ShowDocument.aspx?ID=12371. *See* Requirement 8.2.1.1.

[508] Maradona AF. A Qualitative Exploration of Heuristics and Cognitive Biases in Auditor Judgements. *Accountability*. 2020; 9(2):94-112. doi:10.32400/ja.30634.9.2.2020.94-112; Norcini JJ. Peer Assessment of Competence. *Medical Education*. 2003; 37(6):539-43. doi:10.1046/j.1365-2923.2003.01536.x.

same processes and methods as the FSSP being audited may be more inclined to agree with the processes than an auditor from an FSSP using different methods.

Although some measures are objective and unlikely to be subject to bias (e.g., they are supported by documentation), other decisions are subjective. For example, assessing whether a procedure is appropriate requires specialized knowledge but also a degree of expert judgment, which may differ between auditors and be prone to cognitive biases. Having a team of auditors from different organizations with different types of experience in forensic biology could help to mitigate these and other biases.

Additionally, although some requirements are assessed by finding objective proof of compliance, other requirements call for auditors to depend on the lack of evidence of noncompliance. Because external audits are generally completed in less than one week, by teams unfamiliar with another FSSP's records and procedures, the auditing team will rely on the records provided by the FSSP. Therefore, a lack of evidence of noncompliance should not be used to assert an infallible system.

Likewise, findings for minor infractions may not negatively reflect on the FSSP's technical capabilities, as some findings during audits identify when an oversight in record keeping has occurred. Criminal justice partners should be aware that human factors can impact all aspects of an FSSP's quality system, from selection of standards and implementation to conformance and assessment.

Recommendation 8.1: Teams of at least two individuals from different organizations or with different types or levels of experience in forensic biology should conduct external assessments of forensic DNA laboratories.

8.3 Scientific Quality and Standardization

Assessing the scientific quality of forensic results and methods requires the formulation of a test plan, a demonstration of the integrity of the testing, and the corroboration of the empirical evidence through experimental verification. This process is rooted within the validation testing of an instrument, method, or technique. FSSP personnel should examine and report quality characterizations of methods and instruments such as reliability, validity, and variation. Standardizing a testing method allows the results of an experiment or validation to be reproduced easily, leading to a higher level of confidence of the data produced during routine casework.

Furthermore, while publication remains important to the criminal legal system, scientific quality can also be supported through FSSP personnel critically examining that validation methods and

This publication is available free of charge from: https://doi.org/10.6028/NIST.IR.8503

results, whether published or not, are valid and reproducible and that the conclusions stated are supported with data generated both empirically and statistically.

8.3.1 Variation, Reliability, and Validity

Whenever human judgment and behavior are involved in a process, there will be slight differences in how each analyst completes the necessary tasks and even some variation in how an analyst completes the same task at different times. This natural variation is not error.

QA/QC focuses on variation beyond the level acceptable for producing high-quality results. There are several types of variation that are relevant to scientific quality in forensic science:

1. Variation within an analyst when comparing instances in which they apply the same method or procedure for different materials.
2. Variation between analysts that results from individual differences among analysts.
3. Variation between and within FSSPs due to management, QA/QC processes, training, SOPs, and FSSP personnel.
4. Variation caused by the different materials analyzed in each case.

Reliability is defined as the reproducibility of results over time.[509] The reliability of a specific testing method or instrument is relevant to the question of both inter- and intra-analyst variation. This speaks to the ability of a process to generate the same results over a course of time. Often within an FSSP, the reliability of a testing method or process is monitored using physical controls or physical standards.

Validity refers to an ability to accurately measure what is intended to be measured in a method, process, or theory and to produce results that correctly reflect what the test means (e.g., the extent to which two DNA profiles are similar or different). For a method to be considered valid, it should have been tested under a valid experimental design involving a robust examination of the limitations of the system.

Because the quality of samples in actual casework is highly variable, it is important to note that merely performing a validation to ensure a method or technique works on high-quality samples is insufficient. Studies should test the operating boundaries of a particular system by including sample types and quality seen in casework.

8.3.2 Validation and Requirements to Implement New Practices

In forensic science, reliability is established through the robust validation of instruments, methods, and techniques to determine reliability, precision, uncertainties, and limitations of a

[509] Monteiro EC, Mari L. Preliminary Notes on Metrological Reliability. XXI IMEKO World Congress, Prague, Czech Republic 2015. https://www.imeko.org/publications/wc-2015/IMEKO-WC-2015-TC6-173.pdf

method under differing conditions. Reproducible results should be demonstrated across analysts, materials, and time to ensure results are not the product of random error, unrepresentative samples, or other stochastic issues.

Different study designs may be used depending on the nature of the method or technology being introduced (see **Callout Box 8.2**). This information is used to produce SOPs that are ISO/IEC 17025-compliant and can be used within an FSSP as part of their QMS.

Callout Box 8.2: Validation, Verification, and Evaluation

Validation is an important process within the implementation of new technologies, chemistries, or methods within DNA testing. It is a process by which a method is evaluated to determine its efficacy and reliability for DNA analysis, which includes the following:[510]

Validation: The process by which a method is primarily assessed for:

- its adequacy to suit its intended purpose[511]
- its reliability[512]
- whether it has suitable operational conditions for obtaining results[513]
- its limitations[514]

Within forensic biology, two types of validation processes are commonly referred to:

- *Developmental Validation*: The acquisition of test data and determination of conditions and limitations of a new or novel DNA method for use on forensic samples. Usually conducted by the vendor of the application/technology.[515]
- *Internal Validation*: An accumulation of test data within the FSSP to demonstrate that established methods and procedures perform as expected within the FSSP.[516]

Evaluation: The process by which the suitability of a method is assessed for reliability and reproducibility. This typically occurs when several methods are compared to determine which method is more suitable for an intended task. Ideally, evaluation uses ground-truth-known samples.

A list of standards and guidance documents available for the forensic community to address the validity and reliability of analysis methods can be found in ***Appendix 8.1***.

When designing an internal validation study, FSSPs should separate their validation datasets into two categories:

[510] Federal Bureau of Investigation (FBI). *Quality Assurance Standards for Forensic DNA Testing Laboratories*. 2020. https://le.fbi.gov/file-repository/forensic-qas-070120.pdf/view.

[511] National Association of Testing Authorities. *Guidelines for the Validation and Verification of Quantitative and Qualitative Test Methods. Technical Note 17*. 2012. https://www.demarcheiso17025.com/document/Guidelines%20for%20the%20validation%20and%20verification%20of%20quantitative%20and%20qualitative%20test%20methods.pdf.

[512] Federal Bureau of Investigation (FBI). *Quality Assurance Standards for Forensic DNA Testing Laboratories*. 2020. https://le.fbi.gov/file-repository/forensic-qas-070120.pdf/view.

[513] Ibid.

[514] Ibid.

[515] Ibid.

[516] Ibid.

This publication is available free of charge from: https://doi.org/10.6028/NIST.IR.8503

- Validation/test set: This set is used to examine the limitations of the proposed method. The validation set should be representative of the samples that will be analyzed in the future and should not be used to set the parameters or rules or protocols.
- Training set: This set is used to train, inform, or calibrate the system, model, or protocol. The training set should be different from the validation/test set.

The train-test paradigm protects against overtraining or overfitting models.[517] Overtraining occurs when a model is trained on a dataset that is too small or too similar to the data that it will be used to predict. Overfitting is the instance where there are too many parameters or rules that apply well to the training set but lead to a model or process that is not generalizable to new data. This evaluation should be performed by FSSPs within their laboratory system and SOPs with known samples (i.e., ground-truth data previously generated). This will ensure that the validation study is conducted in a rigorous and reproducible manner.

Through both developmental and internal validation studies, DNA analysts should be able to identify the limitations of the systems they use and when they encounter these limitations during casework. In addition, any evidence samples reported need to fall within the bounds of internal validation. Rulings such as *New York v. Hillary*,[518] in which evidence was excluded on the grounds that the FSSP had not conducted sufficient internal validation studies, clearly demonstrate the potential consequences when data reported fall outside the scope of the internal validation or when validations are not performed.

In examining and identifying the limitations of a method or technology, FSSPs will identify the boundaries in which to operate and the signs when they are approaching those limitations. There are several dangers to consider when performing a validation on nonrepresentative samples. For example, because technical SOPs are directly informed by the validation results, their accuracy and robustness would be impacted by a nonrepresentative sample set. Furthermore, if an SOP does not clearly articulate the limits of the system, DNA analysts may interpret data that fall outside of the validated range, potentially resulting in inaccurate conclusions.

As stated in Standard 8.3.4 of the FBI QAS, "Internal validation studies shall be documented and summarized. Internal validation shall be reviewed and approved by the technical leader prior to implementing a procedure for forensic applications."[519] Additionally, as put forth by Standard 8.3.1.1, validation data may be shared within a multi-FSSP setting, assuming each FSSP completes,

[517] Hastie T, Tibshirani R, Friedman JH. *The Elements of Statistical Learning: Data Mining, Inference, and Prediction*. 2nd ed. Springer: New York, NY, 2009.

[518] County Court of St Lawrence, *The People of the State of New York v. Oral Nicholas Hillary*, (2016). https://www.northcountrypublicradio.org/assets/files/08-26-16DecisionandOrder-DNAAnalysisAdmissibility.pdf.

[519] Federal Bureau of Investigation (FBI). *Quality Assurance Standards for Forensic DNA Testing Laboratories*. 2020. https://le.fbi.gov/file-repository/forensic-qas-070120.pdf/view.

documents, and maintains applicable site-specific precision, sensitivity, and contamination assessment studies.[520] Although the FBI QAS requires external review of validation documents during an audit, this is insufficient to catch errors, unsupported conclusions, or poor experimental design.

Some FSSPs have a dedicated validation section that designs, runs, and documents experiments and uses the results to prepare SOPs and training materials. Alternatively, FSSPs may use student interns, outside companies, or a subsection of its personnel to perform internal validations. In 2022, the National Technology Validation and Implementation Collaborative was established by a group of state and large-local FSSP directors with a common vision to collaborate on validation, method development, and implementation.[521] When individuals performing validation and casework differ, this can lead to unnecessary measurements being made, inappropriate conclusions being drawn, and the possibility of validation missing evaluations of critical aspects of daily casework.

All validation plans should begin with the Technical Leader (TL) determining the individual or group who will perform the work.[522] A testing plan should then be reviewed and approved by the TL prior to validation beginning to ensure all aspects of routine casework are covered and the limitations of the technology are evaluated (see **Callout Box 8.3** for considerations when validating DNA mixtures). Throughout the course of the validation, approval and review of the results, report, and validation package should take place to ensure new and applicable avenues are explored based on the data observed.

Callout Box 8.3: Additional Considerations for Internal Validation of DNA Mixtures

When internally validating DNA mixtures, FSSPs should also:

- Vary the following:
  - Mixture ratios (e.g., 4:2:1, 5:2:2, 4:1:1:1)
    - The same contributor should not be the major (or other location) in every mixture
  - The number of contributors
  - DNA input concentrations to explore the detection and deconvolution limitations
  - Degree of allele sharing
- Design test sample sets to simulate the type of casework samples that are being processed by the FSSP and include samples outside the range that the FSSP might want to analyze with the same method.

[520] Ibid.

[521] Gamette MJ, Wickenheiser RA. Establishment of the National Technology Validation and Implementation Collaborative (NTVIC) and Forensic Investigative Genetic Genealogy Technology Validation Working Group (FIGG-TVWG). *Forensic Science International: Synergy*. 2023; 6:100317. doi:10.1016/j.fsisyn.2023.100317.

[522] European Network of Forensic Science Institutes (ENFSI). *Guidelines for the Single Laboratory Validation of Instrumental and Human Based Methods in Forensic Science, Version 2.0*. 2014. https://enfsi.eu/wp-content/uploads/2017/06/Guidelines-for-the-single-laboratory-Validation-of-Instrumental-and-Human-Based-Methods-in-Forensic-Sciene_2014-version-2.0.pdf.

These test variables need to be assessed in both the internal validation stage and the testing or training phases with the aim of determining the limitations of the DNA typing and interpretation protocol.

8.3.3 Peer Review of Internal Studies

One way that might allow criminal justice partners to review and scrutinize FSSPs' internal study results is through the publication of studies in peer-reviewed journals.[523] However, many peer-reviewed journals do not deem studies that merely demonstrate an FSSP's ability to perform a previously validated procedure as novel or worthy of publication. Furthermore, at best, a full year may elapse between writing, submitting a version for publication, receiving reviewer reports, responding to those reports, making modifications as requested by the journal's editor, and having the article published.[524]

Validation within FSSPs is an ongoing process. With a lack of perceived novelty by peer-reviewed journals prohibiting publication in these journals, the Expert Working Group (EWG) believes that the best way to share this information within the forensic DNA community would be by developing an open-access central repository that could be vetted by a federal nonregulatory agency for scientific quality. The creation of a central repository would enable the scrutinizing of results in a process akin to peer review, as directed by *Daubert*,[525] while maintaining journals' mandates to publish novel scientific literature.

One common concern about sharing data in an external peer review process (e.g., journal publication, calls for data from research agencies) is the privacy protection of individuals sampled to fulfill validation needs. FSSP personnel are sometimes asked to donate these samples. Collecting from personnel generates many potential concerns related to coercion, sample/data privacy, undue influence, and confidentiality. These issues can also prompt assertions that personnel sample collection leads to employees being considered a vulnerable population when recruited to participate in employer-based research.[526]

Federal regulations within the United States and ethical guidelines require safeguards for vulnerable individuals (e.g., employee/supervisor relationships), including the protection of subjects' privacy.[527] FSSPs that choose to collect samples from employees should consult with

[523] Sommer P. Forensic Science Standards in Fast-Changing Environments. *Science & Justice*. 2010; 50(1):12-7. doi:10.1016/j.scijus.2009.11.006.

[524] Ibid.

[525] United States Supreme Court. *Daubert v. Merrell Dow Pharmaceuticals (92-102), 509 U.S. 579*. 1993.

[526] Council for International Organizations of Medical Sciences. *International Ethical Guidelines for Biomedical Research Involving Human Participants*. 2016. doi: doi.org/10.56759/rgxl7405.

[527] United States Department of Health and Human Services. 45 CFR 46: Protection of Human Subjects. Accessed March 27, 2024. https://www.hhs.gov/ohrp/regulations-and-policy/regulations/45-cfr-46/index.html.

FSSP counsel about possibly obtaining written, voluntary, and informed consent. Many ethical, legal, and policy issues should be considered when engaging in personnel collections of biological material, even for the purpose of validation (see **Callout Box 8.4**).[528]

Callout Box 8.4: Ethical Considerations for Biological Specimens Used for Validation

- Research regulations and guidelines require that informed consent take place under conditions that minimize the potential for coercion or undue influence.[529]
- If choosing to collect samples from employees, supervisors should not directly recruit employee subordinates for research participation; recruitment by supervisors should normally occur indirectly, such as by means of general announcements or flyers.[530][490]
- Informed consent should outline all use-case scenarios for each specimen, destruction, or retention of the sample after testing, and if the sample or data will be shared.[531]
- Efforts to prevent the reidentification of the sample to the donor should be in place.
- If data are to be shared, there needs to be considerations for providing protections for the donors.[532]

One way to address ethical and policy issues surrounding the use of biological material in validation studies is for FSSPs to purchase anonymous samples from blood and tissue banks or repositories. These banks often have a resale term within the informed consent that donors sign at collection. These types of samples can be referenced within validation studies completed across multiple platforms and chemistries and can be used to address the ethical and anonymity concerns with data sharing.

FSSPs should avoid purchasing cultured cell lines directly from repositories, as there are inherent issues with stability, use, and imbalance.[533] Purchasing of external materials is particularly helpful if FSSPs have not undergone a human subjects protection certification training or do not have access to an Institutional Review Board (IRB) or expert that can guide and inform the researcher in ensuring that the collection of biological samples from human subjects meets the regulations

[528] Resnik DB. Employees as Research Participants: Ethical and Policy Issues. *IRB: Ethics & Human Research*. 2016; 38(4):11-16.

[529] Grady C. Enduring and Emerging Challenges of Informed Consent. *The New England Journal of Medicine*. 2015; 372(9):855-62. doi:10.1056/NEJMra1411250.

[530] Resnik DB. Employees as Research Participants: Ethical and Policy Issues. *IRB: Ethics & Human Research*. 2016; 38(4):11-16.

[531] Budowle B, Sajantila A. Revisiting Informed Consent in Forensic Genomics in Light of Current Technologies and the Times. *International Journal of Legal Medicine*. 2023; 137(2):551-65. doi:10.1007/s00414-023-02947-w; Chapman W, Hicklin RA, Taylor M. *Beginners Guide to Biometric and Forensic Science Human Subjects Research Protections. NIST Special Publication (Sp) 1289*. National Institute of Standards and Technology,. 2023. doi: 10.6028/NIST.SP.1289. https://nvlpubs.nist.gov/nistpubs/SpecialPublications/NIST.SP.1289.pdf.

[532] Marciano MA, Maynard HP. Enhancing Research and Collaboration in Forensic Science: A Primer on Data Sharing. *Forensic Science International: Synergy*. 2023; 6:100323. doi:10.1016/j.fsisyn.2023.100323.

[533] Borsuk LA, Vallone PM, Gettings KB. STRSeq: FAQ for Submitting. *Forensic Science International: Genetics Supplement Series*. 2022; 8:245-7. ; Lyle JR, Guttman B, Butler JM, Sauerwein K, Reed C, Lloyd C. *Digital Investigation Techniques: A NIST Scientific Foundation Review*. National Institute of Standards and Technology. 2022. *NIST IR 8354*. doi: 10.6028/NIST.IR.8354.

set forth in 28 CFR Part 46[534] or 45 CFR 46.[535] By purchasing human material from commercial vendors, FSSP personnel conducting research have no interaction with the human donors, thereby improving the chance that data can be submitted to an existing publicly available database or published as raw data on the FSSP's own website, provided the subjects have given informed consent.

In efforts to provide ethically collected samples to the forensic DNA community to support validation and training, NIST produced a Research Grade Test Material (RGTM 10235: Forensic Resource Samples), which allows for the public sharing of data and is provided at no cost to FSSPs.[536] Data can be anonymously uploaded to the NIST STRBase data page[537] by users; reported results are then compiled, and the website is frequently updated with new results. These resource samples are available for FSSPs to use in studies and publish data independently of upload to the NIST STRBase page and are meant to support validation and training efforts within an FSSP. The RGTM 10235 is designed to support the forensic DNA community in current and emerging measurement challenges.

If FSSPs desire to collect samples from FSSP personnel for validation testing, they should submit informed consent documentation to an IRB. This informed consent should allow the donor to know what their sample will be used for and to limit the scope of use for each collection. IRBs could help minimize the potential for coercion and undue influence when employees participate in employer-based research and could allow each FSSP to share their validation data for both peer review and for submission in a central repository for validation studies.

8.3.4 Central Repository for Validation Study Results

There is a balance between the costs and benefits of checks within validation that needs to be considered. An internal validation should aim to test the gray areas of a measurement to ensure challenging, complex, or unusual samples that may arise in casework are covered within the FSSP's internal validation.[538] This may include low-level samples, complex mixtures, low-level

[534] GovInfo. *28 CFR 46 - Protection of Human Subjects*. 2022. https://www.govinfo.gov/app/details/CFR-2022-title28-vol2/CFR-2022-title28-vol2-part46/summary.

[535] United States Department of Health and Human Services. 45 CFR 46: Protection of Human Subjects. Accessed March 27, 2024. https://www.hhs.gov/ohrp/regulations-and-policy/regulations/45-cfr-46/index.html.

[536] National Institute of Standards and Technology (NIST). NIST Store: Forensic DNA Resource Samples. 2024, Accessed Feb 5, 2024. https://shop.nist.gov/ccrz__ProductDetails?sku=10235&cclcl=en_US.

[537] National Institute of Standards and Technology (NIST). NIST Research Grade Test Material (RGTM) 10235: Forensic DNA Resource Samples, Information and Ordering. Accessed March 27, 2024. https://strbase.nist.gov/Information/RGTM_10235.

[538] Butler JM. *Debunking Some Urban Legends Surrounding Validation Within the Forensic DNA Community*. Gaithersburg, Maryland, USA. 2006. National Institute of Standards and Technology (NIST). https://projects.nfstc.org/workshops/resources/literature/debunking%20validation%20butler.pdf; Hlinka V, Muharam I, Ientile VK. Chapter 11: Method Validation in Forensics and the Archaeological Sciences. In: Haslam M, Robertson G, Crowther A, Nugent S, Kirkwood L, eds. *Archaeological Science Under a Microscope: Studies in Residue and Ancient DNA Analysis in Honour of Thomas H Loy*. ANU Press: Canberra, Australia, 2009:151-8. doi:10.22459/TA30.07.2009.11.

mixtures, degraded samples, or inhibited samples and is specific for each FSSP and the types of casework observed and tested.

It is imperative that those performing casework or validation have the knowledge to identify when the system fails or when limits are being approached (see ***Sec. 3.3.5: Understanding Upstream and Downstream Effects***). In a QA/QC environment, this understanding of how and why failures occur aids in preventing future failures (see ***Sec. 8.9.1: Training Exercises to Maintain and Increase Expertise***). As Hlinka suggests, "Often a method will appear complex because it can comprise several sub-methods, and it may be necessary then to validate the individual sub-methods as well as the whole system."[539]

In addition to a lack of peer-reviewed publications with validation data available for independent review, many of the available published studies include members of a commercial product development team and are therefore not independent. Although the EWG is not suggesting that developers are performing inadequate developmental validation, there may be a lack of transparent documentation of all experiments performed and issues encountered during developmental validation.

It is important that FSSPs perform robust internal validations to ensure that within their environment and with their analysts and samples, they are achieving suitable results. The purpose of internal validation is to examine the boundaries of a given method within each FSSP structure. In some cases, the results of an internal validation may not be identical to those generated during a developmental validation.

One way to overcome these issues is to create a central repository where data and validation reports can be stored. Such a repository would allow experts to review validations and would promote the sharing of information between FSSPs, which would be beneficial to the DNA community. Furthermore, a validation repository would increase the transparency of validated laboratory operations to external collaborators. This would allow for external insight into how FSSPs performed validations and drew conclusions from the data generated.

This repository would not take the place of internal validation data generated within an individual FSSP system, and such data could not be used other than for a comparison of results across different FSSP systems. One way to promote participation and standardization would be to develop, generate, and curate a standardized sample set that could be provided to FSSPs to supplement their validation efforts.

[539] Hlinka V, Muharam I, Ientile VK. Chapter 11: Method Validation in Forensics and the Archaeological Sciences. In: Haslam M, Robertson G, Crowther A, Nugent S, Kirkwood L, eds. *Archaeological Science Under a Microscope: Studies in Residue and Ancient DNA Analysis in Honour of Thomas H Loy*. ANU Press: Canberra, Australia, 2009:151-8. doi:10.22459/TA30.07.2009.11. p. 156.

These samples would aid the community by anchoring a common test set of samples for comparison between FSSPs. These samples would not take the place of validation samples within an FSSP but would complement ongoing internal validation efforts, allow FSSPs to benchmark their procedures against other FSSPs, and provide community-wide data on success and accuracy.[540]

The American Society of Crime Laboratory Directors has established a validation and evaluation repository with a "goal to compile a list of unique validations and evaluations conducted by FSSPs and universities to foster communication and reduce unnecessary repetition of validations and evaluations to benefit the forensic community."[541] Although this repository is established and accepting submissions, upload of documentation is limited and is dependent on the discretion of FSSPs and universities willing to contribute.

Until there is a paradigm shift in the collection and sample type of biological specimens in validation, privacy and ethical concerns will remain, which will in turn prohibit the sharing of data generated within a validation. See **Callout Box 8.5** for a list of hurdles and benefits of a central repository.

Callout Box 8.5: Hurdles and Benefits for a Validation Repository

Potential hurdles to establish a validation repository:

- Currently there is limited informed consent for any personnel collection
- Changes to how samples are collected are required (e.g., informed consent)
- Purchase, curation, QC, and screening of ethically collected samples for the purpose of validation testing to allow data sharing
- Curation of data is a heavy lift (e.g., who, where, when, what)
- Maintaining or organizing the repository when items become obsolete (i.e., phase-out of technology or methods)
- Currently, forensic science is not an open-access culture. There needs to be a paradigm shift and culture change for this to work and be beneficial (see ***Sec. 12.3*: *Opportunities for Expanding and Improving the Research Culture in Forensic DNA Analysis***)
- Size/storage requirements to house data
- Legislative restrictions on data sharing
- Commercial risks for vendors (e.g., should there be a problem within an instrument, chemistry, algorithm)
- Inappropriate or irrelevant critiques may cause issues in court
- Understanding of data by outside evaluators

[540] Brinkac LM, Richetelli N, Davoren JM, Bever RA, Hicklin RA. DNAmix 2021: Laboratory Policies, Procedures, and Casework Scenarios Summary and Dataset. *Data Brief.* 2023; 48:109150. doi:10.1016/j.dib.2023.109150; Butler JM, Iyer H, Press R, Taylor MK, Vallone PM, Willis S. *DNA Mixture Interpretation: A NIST Scientific Foundation Review. NISTIR 8351-Draft.* 2021. doi: doi:10.6028/NIST.IR.8351-draft.

[541] The American Society of Crime Laboratory Directors (ASCLD). Validation & Evaluation Repository. Accessed March 23, 2024. https://www.ascld.org/validation-evaluation-repository/?title=&keyword=&lab=&discipline=Biology/Serology&state=%5B619%5D.

- Users may not understand the premise behind the data or what was being tested/evaluated and may draw incorrect conclusions
- In the absence of an authoritative body mandating this, some FSSPs will not opt-in

Benefits in establishing a validation repository:

- Strengthen validation efforts within the community by sharing results and data analysis
- Provide FSSPs with a validation framework from other FSSPs, which may increase efficiency
- Increase consistency of "standard validation operations" between FSSPs
- Ensure transparency for the criminal justice system
- May reduce duplication in validation
- Identify gaps within validation (e.g., common pitfalls throughout the community)
- Identify where practices are diverging within the community
- Transparency across all legal system participants
- Allow for baselines for comparison of FSSP processes to identify systemic issues (to determine science issues versus process issues like drift)
- Standardize procedures and reporting of the validation framework and data/testing
- Enable FSSPs to demonstrate community acceptance of a process or technology
- May ease the burden FSSPs face in admissibility hearings

The repository framework could also be used for training manuals, SOPs, reporting templates, and other documents generated across the forensic biology community to increase standardization in practices and reporting.

Other items worth considering in the setup of a validation repository would include upload and sharing of validations that produce negative results or show the technologies or methodologies that did not work effectively. However, it should be noted that one risk of a validation repository would be that the crowdsourcing of information may reduce the independence in evaluation, possibly causing a systematic drift toward individual companies, products, or techniques most used by contributing FSSPs without robust comparison to other available options.

Open-access repositories exist for scientific publications across multiple domains, enabling pre-registration of experimental designs and intended analyses and publication of results and reports. These services could be used more by the forensic community, but because of their large size and multidisciplinary nature, they can contain large numbers of nonrelevant results. As such, a custom, open-access validation repository, fit for DNA analysis, is advisable. This validation repository should contain detailed information about the experimental design, the validation summary, and the generated data used to reach conclusions to allow for effective inter-laboratory comparisons. The information in the repository should be detailed enough that the results can be reproduced from the data and other FSSPs can replicate the methods used without further inquiry.

A validation repository should be housed within a federal, nonregulatory agency with the capabilities of measurement science and statistics and with the ability to review validation

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reports and aid in the facilitation of developing the web-based repository. Establishing an open-access validation repository will require significant funding to achieve. In the meantime, FSSPs should consider publishing their validation studies on their public websites to increase transparency with their criminal justice partners.

Recommendation 8.2: To increase transparency, collaboration, and communication, the forensic DNA community should support and expand development of each of the following:

- **An open-access internal validation data repository that allows forensic science service providers to share validation methods, findings, and data. This repository could be curated by a federal nonregulatory agency that has capabilities in measurement science, statistics, DNA analysis, and data management.**
- **Procedures for the ethical collection of DNA samples by forensic science service providers for research and validation studies and subsequent collection and use of these samples within the open-access validation data repository.**
- **An ethically collected, standardized subset of samples that can aid in facilitating validation work and be uploaded to the open-access internal validation data repository.**

8.3.5 Quality Control

FSSPs often have multiple QC measures in place to detect various forms of error that are known to occur, such as analytical failures, contamination, incorrect processing, or human error. Some of these controls are common across molecular biology laboratories and are not exclusive to forensic science. Others are particular to the discipline because of legislative requirements, accreditation, international standards, or the nature of the work performed in forensic biology.

8.3.5.1 Analytical Controls

No discussion of QA/QC is complete without consideration of analytical controls. The FBI QAS lists analytical controls to include reagent blanks, quantification standards, positive and negative amplification/sequencing controls, allelic ladders, and internal size standards.[542] The purpose of analytical controls is to increase confidence that a method performs as expected. For example, reagent blanks contain all reagents used during sample processing but no DNA sample.[543] Reagent blanks allow an analyst to evaluate if DNA contamination may have occurred during the

[542] Federal Bureau of Investigation (FBI). *Quality Assurance Standards for Forensic DNA Testing Laboratories*. 2020. https://le.fbi.gov/file-repository/forensic-qas-070120.pdf/view.

[543] Sundquist T, Bessetti J. Identifying and Preventing DNA Contamination in a DNA-Typing Laboratory. *Profiles in DNA*. 2005:11-13.

DNA analysis process. Upon completion of analysis in the laboratory, the passing of the controls indicates that the data obtained is valid and can be used for interpretation.

All FSSPs should have written procedures that define the analytical control(s) required for each step of the DNA process, including—at minimum—the controls defined in the FBI QAS and procedures to address and document any controls that do not perform as expected. These written procedures should include when data may be used for interpretation and when or what troubleshooting steps should be performed.[544]

In addition to using the required analytical controls, FSSPs should use appropriate instrumentation, reagents, and software. Before use, the FSSP should demonstrate that these tools perform as expected. For instruments and software (e.g., data analysis, interpretation), this includes the initial validation and subsequent performance checks, as appropriate.[545]

For reagents, this includes the initial validation of the method followed by the verification of each new lot received by the FSSP. The FSSP should determine the instrumentation and reagents requiring these steps and the procedures to be used, including the applicable analytical controls, and define what qualifies as a passing result. Guidance should also be provided on how to address any non-passing results.[546]

8.3.5.2 Physical Standards

Physical standards (e.g., ground-truth-known samples, certified reference materials) are a critical component in ensuring analytical quality, allowing reliable measurements of detection limits, accuracy, and reproducibility. The use of physical standards, beyond the everyday use of positive controls, enhances an FSSP's ability to examine accuracy and consistency of data analysis and reporting between analysts or across a multi-laboratory FSSP system. Datasets such as

[544] Scientific Working Group on DNA Analysis Methods (SWGDAM). *Contamination Prevention and Detection Guidelines for Forensic DNA Laboratories*. 2017. https://www.swgdam.org/_files/ugd/4344b0_c4d4dbba84f1400a98eaa2e48f2bf291.pdf.

[545] Coble MD, Buckleton J, Butler JM, Egeland T, Fimmers R, Gill P, Gusmao L, Guttman B, Krawczak M, Morling N, Parson W, Pinto N, Schneider PM, Sherry ST, Willuweit S, Prinz M. DNA Commission of the International Society for Forensic Genetics: Recommendations on the Validation of Software Programs Performing Biostatistical Calculations for Forensic Genetics Applications. *Forensic Science International: Genetics*. 2016; 25:191-7. doi:10.1016/j.fsigen.2016.09.002; Scientific Working Group on DNA Analysis Methods (SWGDAM). *SWGDAM Guidelines for the Validation of Probabilistic Genotyping Systems*. 2015. https://www.swgdam.org/_files/ugd/4344b0_22776006b67c4a32a5ffc04fe3b56515.pdf; Scientific Working Group on DNA Analysis Methods (SWGDAM). *Validation Guidelines for DNA Analysis Methods*. 2016. https://www.swgdam.org/_files/ugd/4344b0_813b241e8944497e99b9c45b163b76bd.pdf.

[546] Organization of Scientific Area Committees (OSAC). *Standard for Interpreting, Comparing and Reporting DNA Test Results Associated with Failed Controls and Contamination Events, Version 2.0. OSAC Proposed Standard 2020-S-0004*. May 19, 2023, 2021. https://www.nist.gov/system/files/documents/2021/06/01/OSAC%202020-S-0004_Standard_for_Interpreting_Comparing_and_Reporting_DNA_Test_Results_with_Failed_Controls_and_Contanimation%20FINAL%20OSAC%20PROPOSED.pdf.

ProvedIT[547] and NIST Training Data[548] contain ground-truth data that FSSPs can use as a benchmark analysis or training sets.

Physical standards are commonly used within the validation and confirmation of protocols, instrumentation, and technology as required by the FBI QAS.[549] Additionally, they may be used as training datasets. By using a set of universal validation standards incorporated into an FSSP's validation process, the benchmarking of success and performance could be tracked across multiple FSSPs—both nationally and internationally. Universal validation standards could help FSSPs better understand and manage errors or issues that may arise during interpretation or data analysis at the onset of the DNA typing process.

8.3.5.3 Contamination Prevention

Contamination is an ever-present issue for DNA analysis. It can occur at crime scenes and within laboratories and may occur between samples, from personnel to a sample, or from equipment and surfaces to samples. Several analytical and physical controls can detect and prevent contamination such as separation via time or space, the use of negative controls and regular environmental monitoring, and inter-sample and inter-plate checks via software or database solutions.

From a human factors perspective, there are important considerations for both processes and personnel that can help to reduce the incidence and impact of contamination. All personnel involved from collection through reporting should be trained to ensure they are aware of required personal protective equipment (PPE) and how to handle and package materials to minimize cross-contamination.

Observing personnel perform tasks can help them modify behavior and ensure compliance. For example, personnel may not be aware that they are not changing gloves between handling items or equipment, but an observer may detect and correct this oversight via feedback. FSSP workflows and spaces should be set up to minimize the potential for contamination and to provide cues to the analyst as to when to perform key anti-contamination measures, such as keeping glove boxes immediately next to equipment or maintaining separate spaces for reference and evidence samples.

It is important that FSSPs create a nonpunitive culture around contamination detection. Introducing any form of punishment may reduce reporting of contamination events and prevent

[547] Laboratory for Forensic Technology Development & Integration. PROVEDIt Database. Rutgers University. Accessed March 27, 2024. https://lftdi.camden.rutgers.edu/provedit/files.

[548] Gettings KB. Forensic DNA Open Dataset, National Institute of Standards and Technology. Accessed March 27, 2024. https://catalog.data.gov/dataset/forensic-dna-open-dataset-a26bc.

[549] Federal Bureau of Investigation (FBI). *Quality Assurance Standards for Forensic DNA Testing Laboratories*. 2020. https://le.fbi.gov/file-repository/forensic-qas-070120.pdf/view.

improvement opportunities from being identified. When contamination is detected in a sample, the employees involved in the case should assist in the investigation of how the contamination could have occurred—including whether PPE was used, what factors may have contributed to any lapses or omissions in sample handling or PPE use, or other adherence with other contamination minimization procedures (e.g., instrument cleaning, QC of reagents, sterilization of consumables). Contamination events, and the reasons identified for each, should be regularly reviewed to identify trends, with procedures and training updated as necessary.

8.3.5.4 Elimination Databases

FSSPs should have procedures for the detection and control of contamination,[550] and the *SWGDAM Contamination Prevention and Detection Guidelines for Forensic DNA Laboratories* provides extensive guidance on the topic.[551] Given the sensitivity of modern DNA testing capabilities, however, there will be instances where contamination still occurs. As a result, FSSPs should maintain and use an elimination database containing DNA profiles from FSSP personnel and other personnel who may come in contact with evidence or samples that will undergo DNA testing. As the name suggests, an elimination database allows the analyst to eliminate individuals who may have contaminated the sample by virtue of handling or being near the evidence.

FSSP personnel are often aware of the benefits of elimination databases and are generally willing to provide a sample to be uploaded, even if it is not required by their agency. However, where possible and legally permissible, it is important that FSSPs expand sample collection to include crime scene technicians, law enforcement investigators, and emergency response personnel who could be present at a crime scene or interact with evidence.

Lapointe et al. highlight the successes and several casework scenarios resolved by the inclusion of crime scene personnel in the provincial-wide DNA elimination database at the Medical Laboratory in Montreal, Canada (Laboratoire de Sciences Judiciaires et de Médecine Légale).[552] The OSAC *Best Practice Recommendations for the Management and Use of Quality Assurance DNA Elimination Databases in Forensic DNA Analysis* has additional recommendations for personnel to include in such a database.[553]

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[550] Ibid. *See* 9.12.

[551] Scientific Working Group on DNA Analysis Methods (SWGDAM). *Contamination Prevention and Detection Guidelines for Forensic DNA Laboratories*. 2017. https://www.swgdam.org/_files/ugd/4344b0_c4d4dbba84f1400a98eaa2e48f2bf291.pdf.

[552] Lapointe M, Rogic A, Bourgoin S, Jolicoeur C, Seguin D. Leading-Edge Forensic DNA Analyses and the Necessity of Including Crime Scene Investigators, Police Officers and Technicians in a DNA Elimination Database. *Forensic Science International: Genetics*. 2015; 19:50-5. doi:10.1016/j.fsigen.2015.06.002.

[553] Organization of Scientific Area Committees (OSAC). *OSAC 2020-N-0007, Best Practice Recommendations for the Management and Use of Quality Assurance DNA Elimination Databases in Forensic DNA Analysis*. 2021. https://www.nist.gov/system/files/documents/2021/04/01/OSAC%202020-N-0007_Best%20Practice%20Recommendations%20for%20the%20Management%20and%20Use%20of%20Quality%20Assurance%20DNA%20Elimination%20Databases%20in%20Forensic%20DNA%20Analysis_FINAL%20OSAC%20PROPOSED%20REG.pdf.

In the United States, the Genetic Information Nondiscrimination Act of 2008 (GINA) "prohibits employers from requesting, requiring, or purchasing genetic information about applicants or employees, except in very narrow circumstances."[554] GINA includes the following exception:[555]

> Where an employer conducts DNA analysis for law enforcement purposes as a forensic laboratory or for purposes of human remains identification and requests or requires genetic information of its employees, apprentices, or trainees, but only to the extent that the genetic information is used for analysis of DNA identification markers for quality control to detect sample contamination and is maintained and disclosed in a manner consistent with such use.

As such, with some exceptions, FSSPs are permitted to request or require an employee to provide genetic information for QC purposes.[556] Contamination databases should be used and maintained in accordance with applicable laws and FSSP procedures. Additionally, it is important for FSSPs to focus on the QC purposes of these elimination databases, and, except for systemic recurrences that could put future evidence at risk, they should not take punitive action against individuals that are linked to contamination events.

In a joint position statement in 2009, ENFSI, SWGDAM, and the Biology Specialist Advisory Group (BSAG) promoted the maintenance of elimination databases containing FSSP personnel, contractors, manufacturing staff, police personnel, medical examiner and mortuary staff, and unknown profiles in negative controls.[557] The *Best Practice Recommendations for the Management and Use of Quality Assurance DNA Elimination Databases in Forensic DNA Analysis* stresses the importance of elimination databases "to avoid providing misleading information to investigators, entering errant DNA profiles into CODIS, or, more broadly, to detect contaminants."[558]

The ability to identify when a known contaminant is detected in a reagent blank or negative control can assist with remediation, but the additional value of maintaining elimination databases is the ability to detect a contaminant in non-control samples. Unknown profiles on

[554] U.S. Equal Employment Opportunity Commission. Fact Sheet: Genetic Information Nondiscrimination Act. Accessed March 27, 2024. https://www.eeoc.gov/laws/guidance/fact-sheet-genetic-information-nondiscrimination-act.

[555] Cornell Law School Legal Information Institute. 29 CFR § 1635.8 - Acquisition of Genetic Information. Cornell Law. Updated December 20 2018. Accessed March 26, 2024. https://www.law.cornell.edu/cfr/text/29/1635.8.

[556] U.S. Equal Employment Opportunity Commission. Fact Sheet: Genetic Information Nondiscrimination Act. Accessed March 27, 2024. https://www.eeoc.gov/laws/guidance/fact-sheet-genetic-information-nondiscrimination-act.

[557] Gill P, Rowlands D, Tully G, Bastisch I, Staples T, Scott P. Manufacturer Contamination of Disposable Plastic-Ware and Other Reagents - an Agreed Position Statement by ENFSI, SWGDAM and BSAG. *Forensic Science International: Genetics*. 2010; 4(4):269-70. doi:10.1016/j.fsigen.2009.08.009.

[558] Organization of Scientific Area Committees (OSAC). *OSAC 2020-N-0007, Best Practice Recommendations for the Management and Use of Quality Assurance DNA Elimination Databases in Forensic DNA Analysis*. 2021. https://www.nist.gov/system/files/documents/2021/04/01/OSAC%202020-N-0007_Best%20Practice%20Recommendations%20for%20the%20Management%20and%20Use%20of%20Quality%20Assurance%20DNA%20Elimination%20Databases%20in%20Forensic%20DNA%20Analysis_FINAL%20OSAC%20PROPOSED%20REG.pdf.

items of evidence should be compared with an FSSP's elimination database before reporting or uploading a profile to a searchable database of forensic or reference samples. These comparisons may identify the unknown profile as contamination. Failure to do so may mislead investigations or result in misleading reporting or testimony about potential perpetrators. It may also delay or prevent possible retesting of an item to obtain an uncontaminated result.

Identifying contamination through an elimination database also allows the FSSP to investigate the cause or source of the contamination event to potentially make process improvements or further educate their personnel. Additionally, associating an unknown profile to a contaminant event prevents the upload and searching of that profile in a DNA database. Just as importantly, it also prevents the unnecessary expenditure of resources (both in the forms of finances and personnel time) to investigate a potential connection between two (or more) unrelated cases due to a contaminating profile when such an event could have been prevented if associated to an elimination database sample prior to upload.

Although not associated with law enforcement officers or FSSP personnel, one of the most notorious stories of DNA contamination leading to the investigation of unrelated cases is the "Phantom of Heilbronn" in Germany, where an investigation into 40 cases ultimately led to the discovery of contamination by a factory worker employed to package cotton swabs used to collect the DNA samples.[559] As a result of contamination events traced back to manufacturing staff, the ENFSI, SWGDAM, and BSAG joint position statement requested that manufacturers of consumables and products to be used in DNA analysis take additional precautions to prevent contamination in the manufacturing process and proposed a new product grade be introduced.[560]

This joint position statement became the basis for the ISO/IEC 18385 standard.[561] ISO/IEC 18385 specifies "requirements for the production of products used in the collection, storage, and analysis of biological material for forensic DNA purposes," including the consumables and reagents used for evidence collection (i.e., swabs, containers, and packaging) and the analysis of DNA samples (i.e., tubes and other plasticware, disposable laboratory coats, gloves, and other consumables) that do not require cleaning for continued use.[562]

[559] Himmelreich C. Germany's Phantom Serial Killer: A DNA Blunder. *Time*. 2009. Accessed March 27, 2024. https://content.time.com/time/world/article/0,8599,1888126,00.html

[560] Gill P, Rowlands D, Tully G, Bastisch I, Staples T, Scott P. Manufacturer Contamination of Disposable Plastic-Ware and Other Reagents - an Agreed Position Statement by ENFSI, SWGDAM and BSAG. *Forensic Science International: Genetics*. 2010; 4(4):269-70. doi:10.1016/j.fsigen.2009.08.009.

[561] Promega. Forensic-Grade Products for Human Identification: Preparing for ISO 18385 Requirements. Accessed March 27, 2024. https://www.promega.com/resources/profiles-in-dna/2014/forensic-grade-products-for-human-identification/#RelatedResourcesId-9273fe46-d63f-4c23-be66-e2fba4f5f333.

[562] International Organization for Standardization (ISO). *Minimizing the Risk of Human DNA Contamination in Products Used to Collect, Store and Analyze Biological Material for Forensic Purposes. ISO 18385:2016* 2016. https://www.iso.org/standard/62341.html.

ISO/IEC 18385 also specifies a requirement for manufacturers to minimize the risk of occurrence of detectable human nuclear DNA contamination in products used by the global forensic science community. Manufacturers that demonstrate compliance with the standard are able to label their products as "ISO/IEC 18385 Forensic DNA Grade," but the standard also requires that manufacturers have procedures for notifying customers if products are "subsequently found to have failed the product specifications or where the quality of the product has been impacted."[563]

In addition to the elimination databases maintained at the FSSP level, many manufacturers maintain an elimination database that may be available to customers or searchable upon request.[564] ISO/IEC 18385 requires a policy for the collection of voluntary reference samples from personnel as allowed by the jurisdictional regulations but also provides guidance to the International Commission on Missing Persons as a secure repository for DNA profiles of employees.[565]

Recommendation 8.3: When possible and legally permissible, forensic science service providers should promote the development, maintenance, and use of elimination databases containing DNA profiles from forensic science service provider personnel and other personnel (e.g., crime scene technicians, law enforcement investigators, and emergency responders) who may come into contact with evidence or samples that are collected for DNA testing. Forensic science service providers should search unknown profiles against this elimination database before reporting or uploading to other forensic or reference sample databases.*

*See footnote[566] for qualified support.

8.4 Internal Review

Having a qualified person or analyst review the results and opinions of a forensic analysis is one of the most fundamental measures of preventing analysis and reasoning errors. Standards such

[563] Ibid. *See* Product packaging, labelling, and documentation, 10; Quality management systems, 5.5.

[564] Promega. Forensic-Grade Products for Human Identification: Preparing for ISO 18385 Requirements. Accessed March 27, 2024. https://www.promega.com/resources/profiles-in-dna/2014/forensic-grade-products-for-human-identification/#RelatedResourcesId-9273fe46-d63f-4c23-be66-e2fba4f5f333.

[565] International Organization for Standardization (ISO). *Minimizing the Risk of Human DNA Contamination in Products Used to Collect, Store and Analyze Biological Material for Forensic Purposes. ISO 18385:2016* 2016. https://www.iso.org/standard/62341.html. *See* Quality Management Systems, 5.7 (note 3).

[566] One EWG member (David Kaye) expressed support for creating and using elimination databases as described in the recommendation. However, he believes that limiting the recommendation to that which is currently "possible and legally permissible" is unclear and too confining. In his view, the recommendation should include the statement that, if laws such as the federal Genetic Information Nondiscrimination Act of 2008 inhibit the creation of these databases, then the law-enforcement and forensic-science communities should seek legislation to amend them.

as ISO/IEC 17025[567] mandate the use of casework reviews, with the aim of ensuring that procedures have been followed, that results and data support the conclusions drawn, and that errors are prevented.

Commonly, internal review in forensic casework can be split into three distinct tasks: (1) administrative review of case files and reports; (2) technical peer review of processes, results, interpretations, and opinions; and (3) verification. Each task has distinct purposes and is aimed at detecting, and ultimately correcting, different types of errors.

A full peer-review process should incorporate all three types of review, ensuring that the opinions formed are fully supported by the results and data; that scientifically valid processes have been used; that all actions performed are adequately documented; and that there are no errors in reasoning, documentation, or analysis that may affect the results. To achieve these aims, however, the peer-review process should be carefully designed by considering known or potential sources of error, including human error, human factors issues, workflow efficiency, and customer requirements.

8.4.1 Administrative Review

An administrative reviewer confirms that the non-technical aspects of a case file are complete according to SOPs, that all the required documentation is present, and that the final report is coherent and free from grammatical and spelling mistakes. Administrative reviews are required by the FBI QAS[568] and the Australian standard on reporting, AS5388.4,[569] without explicit restriction on who may conduct this form of review. As such, if it does not involve checking of technical data, it may be conducted by administrative personnel or individuals not authorized in the specific techniques used in the case, but reviewers should be familiar with their FSSP's protocols and QMS.

8.4.2 Technical Peer Review

A technical reviewer ensures all technical results and interpretations are scientifically sound, supported by data, and produced via validated processes. This may include a review of the procedures and processes used; the data and results obtained; the interpretations applied; and

[567] International Organization for Standardization (ISO). *General Requirements for the Competence of Testing and Calibration Laboratories, ISO/IEC 17025:2017*. 2017. https://www.iso.org/standard/66912.html.

[568] Federal Bureau of Investigation (FBI). *Quality Assurance Standards for Forensic DNA Testing Laboratories*. 2020. https://le.fbi.gov/file-repository/forensic-qas-070120.pdf/view.

[569] Standards Australia. *Forensic Analysis Reporting. AS 5388.4-2013* 2013. https://infostore.saiglobal.com/en-us/standards/as-5388-4-2013-120014_saig_as_as_251524/.

the documentation of the reasoning, assumptions, and limitations. Such reviews should be conducted by individuals authorized[570] and knowledgeable in the techniques used.

Any changes in conclusions or disagreements resulting in conflict resolution should be clearly documented in the case file and easily identifiable by end-users. Technical reviews should be conducted independently from the primary analyst and be thoroughly documented to enable a clear determination of what was queried or changed.

8.4.3 Verification/Independent Reexamination

In most forensic disciplines, the term *verification* refers to an independent reexamination of results and interpretations conducted by a second authorized examiner. A verification may be performed during a technical review or as a separate step within the wider review process. For example, latent print examination uses the ACE-V process: Analysis, Comparison, Evaluation, and Verification.[571]

Within DNA analysis workflows, verification processes may be used to confirm the accuracy of genotyping or to obtain an independent opinion on the number of contributors (NOC) to a profile. These checks may occur during the workflow, before progressing to the next stage, or at the end as a part of the technical review. However, they are distinct from the technical review, as they represent a reanalysis of the decisions and interpretation, rather than a confirmation that the opinion reached is supported by the data available. Performing these checks on critical interpretations prior to progressing with the workflow can assist in detecting errors or omissions in an efficient manner, preventing downstream processing from being performed on inaccurate data.

8.5 Blinded Reviews

A second analyst may perform a blinded verification, whereby they are unaware of the first analyst's thought processes or opinions. Blinded verification helps decrease exposure to task-irrelevant contextual information. Alternatively, it may be performed non-blind, wherein the second analyst is aware of the first analyst's opinions and has access to the case notes and files.

Blind verification is generally considered to be more likely to detect errors and omissions because it can help limit confirmation bias and enable more independent decisions. It may also reduce

[570] Federal Bureau of Investigation (FBI). *Quality Assurance Standards for Forensic DNA Testing Laboratories*. 2020. https://le.fbi.gov/file-repository/forensic-qas-070120.pdf/view. The FBI QAS allows an individual who is a previously qualified analyst to perform technical reviews, provided the technical reviewer meets the requirements of and is proficiency-tested in accordance with the applicable standards.

[571] Expert Working Group on Human Factors in Latent Print Analysis. Latent Print Examination and Human Factors: Improving the Practice through a Systems Approach. National Institute of Standards and Technology; 2012. doi:10.6028/NIST.IR.7842

the effects of authority bias, anchoring, and hindsight bias.[572] However, because it may increase the time required within the workflow, a risk-based approach can be taken to either review blind only critical decisions or only cases deemed high risk. In the former, decisions that may critically impact the outcome can be reviewed blind, such as genotyping the DNA profile or assignment of NOC, but the review of rest of the process is non-blind.

Where it is feasible for FSSPs to do so, an assessment of the potential impact of an error should be taken into account. For example, knowledge that a case contains only DNA evidence, or hinges on a single result or sample, may cause an FSSP to select a fully blind review. However, it may be rare for FSSPs to have this knowledge, particularly in the early stages of a case. Therefore, policies may need to be tailored based on the information that is within the remit of the FSSP, such as number or nature of samples or results, type of crime (e.g., serious or violent crime), or nature of analysis (e.g., activity-level reporting).

If a risk-based approach is taken to blinding reviews, criteria for blind versus non-blind review should be defined and documented in advance and should not be based on specific case results but on the risk associated with the case type, nature of result (e.g., complex mixtures versus single source profiles), or process segment (e.g., NOC or probabilistic genotyping software [PGS] output interpretation). Furthermore, depending on the resources available and the risk associated with a decision or processes, different forms of blinding can be employed.

8.5.1 Double-Blind

In a double-blind review, the reviewer performs a second, independent analysis, unaware that they are acting as the verifying analyst and therefore unaware of the first analyst's opinions, identity, or seniority/perceived level of expertise. In this system, two analysts perform the analysis and interpretation at the same or similar times, and the results are collated and compared by a third independent analyst or administrator. Task-irrelevant contextual information may also be stripped from the information provided to the analysts to prevent contextual bias.

An example of a double-blind review is where two analysts independently genotype DNA profiles, with the results compared automatically by genotyping software following the completion of typing. Neither analyst knows, nor can be influenced by, the opinion of the other. Double-blind review can also be used to mitigate authority biases or interpersonal differences, because the reviewer is unaware of the identity of the analysts, and therefore issues of seniority or interpersonal feelings cannot affect the review process and outcomes.

[572] *Authority bias*: tendency to be more influenced by the opinion of an authority figure, unrelated to the content of the opinion. *Anchoring*: tendency to rely too heavily on the first piece of information they receive about a topic. *Hindsight bias*: tendency to perceive past events as having been more predictable than they were.

8.5.2 Single-Blind

In a single-blind review, the reviewer performs an independent analysis, unaware of the first analyst's opinions but aware that they are acting as a reviewer. Depending on the system employed, they may be unaware of the identity of the primary analyst. Task-irrelevant information may also be stripped prior to review. This type of review may be encountered when determining NOC or suitability for analysis—reviewers may be blinded to the first analyst's decision, but they are aware that they are reviewing a profile where a decision has already been made.

Although blinding to the original opinion may reduce the risk of confirmation bias, bias may occur in cases where the evidence is on the threshold of what can be analyzed by an FSSP. For example, if five-person mixtures cannot be interpreted according to SOPs, a reviewer may subconsciously infer that the first analyst concluded the sample was a four-person mixture—otherwise it would not have progressed to review. Therefore, FSSPs need to take care that negative decisions (i.e., those that stop the interpretation process) are also reviewed.

8.5.3 Non-Blind

In a non-blind review, the reviewer is aware of the opinions and identity of the reporting analyst and has access to the case file and associated documentation. Potential examples of a non-blind review include technical reviews of entire case files, where all information is needed to scrutinize decisions and opinions, or a review of NOC assignments, when the reviewer is aware of the opinion provided by the primary analyst.

8.5.4 Considerations Regardless of Review Type

Each type of review blinding has different benefits and resource implications. For this reason, uptake of blinding is currently relatively low and, in the FSSPs where it is implemented, how blinding is conducted is variable. An efficient *and* effective peer-review system may use a combination of blinding approaches for different stages and aspects of the review process, depending on the criticality of the results being reviewed.

For example, critical results may be defined as those that have the potential to alter the direction or weight of the opinion, such as determining genotypes and estimating NOC. Other decisions in the case may be critical to the final opinion but may be less subject to some forms of bias, such as sampling decisions. These decisions would not require blind review, because little or no benefit would be gained.

Decisions that will not impact the final opinion, or where any issues would be irreversible, such as choice of extraction method, may also not require blind review. Single-blind review may be

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used to scrutinize PGS outputs and suitability, because the reviewer would be aware that interpretation had already been performed. Non-blind review may be used for technical review of case files, as the reviewer requires access to the complete case file and material to place results and decisions in the broader case context.

Depending on the FSSP's processes, and particularly the LIMS in place, blinding may be easily achieved with minimal resourcing impact, or it may require separate administration and result collation. At a minimum, the EWG recommends that decisions that may impact the direction or weight of the final opinion are reviewed in a single-blind manner; however, double-blind approaches are optimal to minimize contextual bias.

Because it is not possible to know whether a particular decision impacts a final opinion without knowing the decision (and thus rendering blinding impossible), FSSPs could approach blinding on a task level—selecting critical tasks that may generate decisions that impact opinions. Examples of these tasks include the decision of whether a DNA profile is suitable for comparison, NOC assignment, or scrutinization of the PGS output to decide if the output is consistent with the input.

Non-critical tasks, at least for blind review, may be equally as important for ensuring quality and consistency, but an error would not materially affect the opinion. Examples include checking documentation, completing forms, or ensuring that the negative and positive controls have been run with the samples.

8.6 Review Processes and Mechanisms

FSSPs should take care to design review processes and associated documents that promote active reviewing and direct attention to results that may change the weight or direction of opinions. Designing forms that direct the technical and administrative reviewers' attention to critical aspects can assist in ensuring that high-risk errors or omissions are detected. This may involve requiring reviewers to enter specific information (e.g., likelihood ratio [LR] obtained, date of processing) into the form to promote active reviewing (see ***Sec. 11.3.4: Distractions and Interruptions***).

Alternatively, some checks could be automated through LIMS or through the application of specific tools within programs such as genotyping software. Examples include designating peaks as allelic or artifactual, assigning the NOC with appropriately validated software, or checking probabilistic genotyping diagnostic information through automated checking programs.

8.6.1 Checklists

Checklists can be highly useful tools to detect and reduce errors. As a tool to aid human cognition, particularly for repetitive tasks, checklists can assist in preventing errors of omission, direct

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attention to priority areas, and provide information on the sequence reviews should take.[573] Data from the medical domain on the effectiveness of checklists are mixed; although they show checklists are correlated with better patient outcomes, including lower incidence of post-operative mortality, these results may reflect the quality of hospitals using checklists rather than the effects of checklists themselves.[574]

Many FSSPs have adopted the use of checklists, but care is required to ensure that they are designed and used appropriately. Adding all potential tasks to a checklist or expanding the list every time an error is detected can result in long, unwieldy forms that may have the opposite effect to that intended, reducing attention, and promoting automaticity in checking the form. For example, pilots have reported errors occurring from conducting checks from memory rather than using the long forms for each task.[575]

Likewise, proofreading checklists were more prone to miss errors if presented in a fixed order that participants got used to, while checklists that varied in order or specifically alerted the reviewer to errors gave more favorable outcomes.[576] A failure to use the checklist at all, not completing the checklist, being distracted during the completion of the checklist, and a lack of training on the use of the checklist were some of the reasons noted as contributing factors to aviation incidents and near-misses.[577]

There may also be a large quality and administrative burden with the use of checklists, as they require development, validation, and regular updating as processes or technology changes. Checklists are recommended for tasks that require precision and strict sequential approaches but cannot replace experience and focus and are often only part of potential reviewing solutions. Examples of where checklists may assist include the analytical processing of DNA samples via robotic platforms, where samples and consumables should be added in defined orders with the correct location and solution, or in the review of report contents, where specific content should always be present.

The introduction of substantial checks on a process or an analyst's decisions may have unintended consequences. For example, reviewers may assume that the use of checklists or standardized processes automatically results in compliance and appropriate decisions and

[573] National Commission on Forensic Science. *Views of the Commission: Use of Checklists in Forensic Science*. 2017. https://www.justice.gov/archives/ncfs/page/file/1004656/dl.

[574] Abbott TEF, Ahmad T, Phull MK, Fowler AJ, Hewson R, Biccard BM, Chew MS, Gillies M, Pearse RM, International Surgical Outcomes Study g. The Surgical Safety Checklist and Patient Outcomes after Surgery: A Prospective Observational Cohort Study, Systematic Review and Meta-Analysis. *British Journal of Anaesthesia*. 2018; 120(1):146-55. doi:10.1016/j.bja.2017.08.002.

[575] Degani A, Wiener EL. *Human Factors of Flight-Deck Checklists: The Normal Checklist*. NASA Contractor Report 177549. 1990:1-71. https://ntrs.nasa.gov/api/citations/19910017830/downloads/19910017830.pdf.

[576] Barshi I, Healy AF. Checklist Procedures and the Cost of Automaticity. *Memory and Cognition*. 1993; 21(4):496-505. doi:10.3758/bf03197181.

[577] NASA Aviation Safety Reporting System (ASRS). *Database Report Set - Checklist Incidents*. 2022. https://asrs.arc.nasa.gov/docs/rpsts/chklist.pdf.

therefore may be less critical in their review of the case file or data. Studies within the medical domain have shown that peer checks can promote diffusion of responsibility and gives a false sense of safety, given that errors still occurred even with double-checks taking place.[578]

8.6.2 Split Reviews

There is also a risk of fatigue, inattention, slips, lapses, and omissions affecting the review process, particularly with large case files. Therefore, it may be advisable to split the review process across multiple sessions or individuals. This approach, however, may require allocation of additional FSSP resources and personnel, and may impact criminal justice partners.

Batching samples and reviewing as stages are completed can expedite review and minimize the fatigue that can occur when reviewing a large case. Reviewing each stage of the process as it is performed can also increase efficiency and cost-effectiveness by detecting and rectifying any errors as they occur. For example, verifying allelic designations and NOC assessments before interpretation and comparison may indicate if the profile is unsuitable for comparison, if reamplifications are required, or if an error has occurred during genotyping (see ***Sec. 3.4: Generating a DNA Profile and Determining Suitability for Interpretation***).

8.6.3 Conflict Resolution

FSSPs should have documented policies or procedures to address any disagreements that may arise during the review process, as well as how those disagreements and resolutions will be documented in the case file. The policy or procedure should include clear definitions of what a disagreement is and differentiate between consultation and disagreement resolution. For example, a disagreement may be defined as a lack of consistency in results or opinions, where two analysts hold different views of the NOC to a DNA profile or the classification of a peak within an electropherogram (EPG). The definition should focus on the potential outcome (e.g., differing opinions or opinions in agreement) rather than the reasons for the disagreement (e.g., lapse in attention resulting in an oversight or omission of a key fact or finding from final opinions).

Selecting the review process based on the nature of the disagreement may allow biases to creep into the process or for errors to be minimized. For example, a difference in NOC determination may occur due to an analyst simply overlooking a minor contributor allele or may occur due to a fundamental difference in reasoning. Allowing differences in NOC determination to be resolved first via a conversation between analysts (to determine if the difference is due to an omission or a genuine difference) risks allowing more senior analysts to influence more junior analysts' decisions (authority bias). It may also promote selecting the "easier" option of the two (just

[578] Schwappach DLB, Taxis K, Pfeiffer Y. Oncology Nurses' Beliefs and Attitudes Towards the Double-Check of Chemotherapy Medications: A Cross-Sectional Survey Study. *BMC Health Services Research*. 2018; 18(1):123. doi:10.1186/s12913-018-2937-9.

agreeing rather than going to a different reviewer, particularly if there are time pressures for reporting). Finally, it may allow a consultation between analyst and reviewer to occur before conclusions are documented, resulting in differences not being recorded within the case file.

The FSSP should develop a process by which the DNA analyst's and reviewer's opinions are assessed for consistency, with clear guidance for who should collate the two analyses (e.g., administrative personnel versus analysts); what constitutes a disagreement; and whether the disagreement should be resolved by a conversation between the analyst and the reviewer, a third independent analysis, or a mediation by a senior analyst. Consultations, where an analyst seeks guidance or advice from a separate analyst (not the technical reviewer) prior to forming their opinion, may be excluded from the formal conflict resolution pathway but should be recorded in the case file.

Different processes may be used for different results, depending on their potential impact on the case, the efficiency of performing reexaminations, and the availability of independent examiners. Regardless of the process used, all reviews, disagreements, methods of resolution, and outcomes should be documented in the case file and be readily identifiable by end-users. Unresolved disagreements should be disclosed in reports.

Recommendation 8.4: To maximize the potential to detect errors and omissions, forensic science service providers should ensure that technical review processes include steps to mitigate review bias, direct attention to important decisions for review, consider fatigue, consider difficult case reviews, and identify appropriate methods to resolve and document disagreements.

8.6.4 Reviewer Competency

Performing an effective peer review requires specific skills, training, monitoring, and feedback. The skill set required to perform a task is not necessarily the same as the skill set required to review another analyst's performance at that task. As such, it is necessary to provide training in how to conduct technical and administrative reviews. This should include practical training and assessment on the FSSP's review and disagreement resolution processes, the consequences of inappropriate or incomplete review, and the biases that may occur during the review process.

8.6.5 Review Stringency

The FBI QAS currently requires technical and administrative review on all case files and reports to ensure opinions and supporting data are reasonable and within the constraints of scientific

This publication is available free of charge from: https://doi.org/10.6028/NIST.IR.8503

knowledge.[579] ISO/IEC 17025 allows an FSSP that has performed a risk assessment to reduce their percentage of cases to review.[580]

An FSSP not required by the FBI QAS to review all cases should consider factors that can influence the chance of error, or the impact of any error, such as the following (see also ***Sec. 8.10.1*: Risk Analysis**).:

- Case size and complexity
- The methods being applied, and the nature of the samples processed
- Case priority or potential probity of results
- The experience, competency, and frequency with which the analyst performs the primary analysis

If FSSPs are going to reduce review requirements, that should be based on the risk profile of the case. For example, blind review or reexamination may be used in cases the FSSP has deemed to be higher risk (e.g., based on perceived case complexity due to size, nature of samples or profile), whereas non-blind review could be used on lower-risk cases.

Risk assessments can be performed across an FSSP's delivery offerings at a high level based on task accuracy (informed by validations and competency/proficiency testing), frequency of tasks, complexity of tasks, and amount of data. Detailed guidance may allow a case-by-case assessment to be performed at the case acceptance stage, where cases deemed small, low-risk, simple, and frequent may undergo a reduced review. However, it is noted that this may reduce the potential for detection and correction of errors. Analysts should note the case review status and the review methodology used in the case file.

8.6.6 Monitoring the Effectiveness of Review Processes

FSSPs should regularly monitor their review programs' effectiveness to ensure they are detecting and correcting errors. This monitoring may be incorporated into existing proficiency testing programs or could be a separate system test through the provision of case files with known errors. Mock case files with deliberately inserted errors can be introduced into review workflows, preferably in a blinded manner, to test that analysts are reliably detecting various errors in analysis, interpretation, or reporting.

The aspects being detected in review should be monitored to determine if trends are emerging, either within an individual analyst's case files or competence, or across a group of analysts. The

[579] Federal Bureau of Investigation (FBI). *Quality Assurance Standards for Forensic DNA Testing Laboratories*. 2020. https://le.fbi.gov/file-repository/forensic-qas-070120.pdf/view. See Standard 12.1.

[580] National Association of Testing Authorities. *Specific Accreditation Criteria ISO/IEC 17025 Application Document Legal (Including Forensic Science) - Appendix*. 2023. https://nata.com.au/files/2021/05/Forensic-Science-ISO-IEC-17025-Appendix-effective-feb-2020.pdf.

This publication is available free of charge from: https://doi.org/10.6028/NIST.IR.8503

detection of a sustained pattern of errors requiring correction may prompt remedial training for all analysts or a redesign of processes to prevent the error from reoccurring. The FSSP should also determine whether the potential for undetected errors in casework would require corrective action (see ***Sec. 8.10.2*: *Corrective Actions***).

8.7 Testimony Review

In addition to ensuring that analysts maintain the technical skills to complete DNA testing and interpretation of DNA mixtures, it is important to ensure that analysts provide accurate testimony (see ***Chapter 6*: *Pre-Trial Preparation and Testimony***). Although written reports undergo technical and administrative review, the testimony provided pertaining to the results and opinions in these reports relies solely on the testifying analyst. Testimony should be supported by the data for the items tested, be within the bounds of the analyst's expertise and the FSSP's validation and SOPs, and have the appropriate scientific literature to support the opinions and interpretations presented.

ANAB accreditation requirements specify that the FSSP's procedures for review of results should include testimony and specifies that the procedure should ensure the "opinions and interpretations are accurate, properly qualified and supported by the technical record."[581] Although ANAB accreditation requirements do not specify a frequency, the FBI QAS specifically requires the FSSP to annually review the testimony of each analyst;[582] the EWG supports an annual requirement.

ANAB accreditation requires that individuals who perform review of testimony meet competency requirements for the testing tasks being reviewed but does not require that the individuals be employed by the FSSP, be proficient in the technique, or be currently performing the work being reviewed.[583] The testimony review should ensure scientific accuracy, but reviewers should also consider if the testimony provided was understandable to an end-user. The FBI QAS does not specify requirements for the reviewer but does require that the review be documented and provided to the testifying individual and that any deficiency or corrective action be documented.[584]

[581] ANSI National Accreditation Board (ANAB). *AR 3125: Accreditation Requirements for Forensic Testing and Calibration (2023)*. 2023. https://anab.qualtraxcloud.com/ShowDocument.aspx?ID=12371. *See* 7.7.1.I.

[582] Federal Bureau of Investigation (FBI). *Quality Assurance Standards for Forensic DNA Testing Laboratories*. 2020. https://le.fbi.gov/file-repository/forensic-qas-070120.pdf/view. *See* Standard 16.2.

[583] ANSI National Accreditation Board (ANAB). *AR 3125: Accreditation Requirements for Forensic Testing and Calibration (2023)*. 2023. https://anab.qualtraxcloud.com/ShowDocument.aspx?ID=12371. *See* 6.2.3.2.

[584] Federal Bureau of Investigation (FBI). *Quality Assurance Standards for Forensic DNA Testing Laboratories*. 2020. https://le.fbi.gov/file-repository/forensic-qas-070120.pdf/view.

Testimony monitoring policies or procedures should address actions required if an analyst testifies outside the limits of their expertise or of science. Within the testimony review procedures, FSSPs should also include requirements in case an analyst goes a specified interval without testifying. For example, if an analyst goes three years without being reviewed or testifying, they should participate in a practice testimony or a moot court exercise.

8.8 Proficiency Testing

Within calibration and testing laboratories, proficiency testing is specifically defined as a means for evaluating participant performance against preestablished criteria through inter-laboratory comparisons.[585] The ISO/IEC 17043:2023 standard for general requirements for proficiency testing states the purpose of such testing, including the following:[586]

1. Evaluation of the performance of laboratories for specific tests or measurements and monitoring laboratories' continuing performance.
2. Identification of problems in laboratories and initiation of actions for improvement that, for example, may be related to inadequate test or measurement procedures, effectiveness of personnel training and supervision, or calibration of equipment.
3. Establishment of the effectiveness and comparability of test or measurement methods.
4. Identification of inter-laboratory differences.

FSSPs accredited to ISO/IEC 17025 or ISO/IEC 17020 are required to monitor their performance via comparison with results of other FSSPs where available and appropriate. This monitoring predominantly occurs within forensic biology via participation in proficiency tests. Commercial proficiency test providers such as Collaborative Testing Services Inc. (CTS), International Quality Assessment Scheme (IQAS), and Forensic Assurance offer a range of biological proficiency tests, including body fluid identification, DNA profiling, and probabilistic genotyping.

Externally provided proficiency tests afford an increased level of independence compared with internally administered tests, allow for inter-laboratory comparisons on comparable items with the same ground-truth and level of difficulty, and require lower levels of resourcing from individual FSSPs. Such tests provide important data on the ability for FSSPs to achieve accurate results on standardized samples processed with specific techniques.

[585] International Organization for Standardization (ISO). *General Requirements for the Competence of Testing and Calibration Laboratories, ISO/IEC 17025:2017*. 2017. https://www.iso.org/standard/66912.html.

[586] International Organization for Standardization (ISO). *Conformity Assessment: General Requirements for the Competency of Proficiency Testing Providers, ISO/IEC 17043:2023*. 2023. https://www.iso.org/standard/80864.html.

Current test designs allow systematic issues in procedures, environment, training, or equipment to be identified, investigated, and corrected.[587] Proficiency tests also allow feedback to be given to participants regarding their performance against ground-truth and other FSSPs, which can be valuable for identifying improvement opportunities.

Open, externally provided proficiency tests do not fulfill all requirements of performance testing and have notable restrictions that prevent the test results from informing the true limits of end-to-end system performance, practitioner competence, or decision-making appropriateness. A fundamental restriction of proficiency testing is the need to provide standardized samples of a specific nature (e.g., quality or quantity, ability to give conclusive opinions) that allows FSSPs to obtain meaningful results, regardless of the systems and procedures they use.[588]

At least one proficiency testing organization has acknowledged that there is commercial pressure from FSSPs to ensure tests are "easy"—testing the minimal level of competence needed to perform at a satisfactory level.[589] Given these pressures, the current requirement within the FBI QAS to perform two proficiency tests per year may not be providing all the benefits expected, and some of the effort and cost may be better spent on improving available proficiency tests and on additional forms of training exercises or collaborative trials (see ***Sec. 8.9*: Provision of Practice and Feedback Opportunities for Expertise Development).**

The Forensic Science Regulator specified that tests should contain poor-quality, mixed, and potentially uninterpretable samples to test challenging yet frequently encountered factors.[590] Such tests are, at present, difficult to obtain from commercial providers. The necessity to test on these types of samples was also specifically noted by the draft *NIST Scientific Foundation Review on DNA Mixture Interpretation*.[591] This review found that current proficiency tests, even for mixture tests, consist of simple mixtures with high-quality and high-quantity DNA. This report recommended that tests should include mixtures with low-template components and samples with more than two contributors. It is important that results should not be extrapolated to infer either validity or competency on these challenging sample types when not included in test designs.

[587] Expert Working Group for Human Factors in Handwriting Examination. Forensic Handwriting Examination and Human Factors: Improving the Practice through a Systems Approach. NIST IR 8282r1. National Institute of Standards and Technology; 2021. doi:10.6028/NIST.IR.8282r1

[588] Pierce ML, Cook LJ. Development and Implementation of an Effective Blind Proficiency Testing Program. *Journal of Forensic Sciences*. 2020; 65(3):809-14. doi:10.1111/1556-4029.14269.

[589] President's Council of Advisors on Science and Technology (PCAST). *Report to the President: Forensic Science in Criminal Courts: Ensuring Scientific Validity of Feature-Comparison Methods*. 2016. https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/PCAST/pcast_forensic_science_report_final.pdf.

[590] Forensic Science Regulator. *Guidance: Proficiency Testing Guidance for DNA Mixture Analysis and Interpretation. FSR-G-224, Issue 1*. 2020. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/894598/G224_DNA_Mix_PT_Guidelines__Issue1_2020.pdf.

[591] Butler JM, Iyer H, Press R, Taylor MK, Vallone PM, Willis S. *DNA Mixture Interpretation: A NIST Scientific Foundation Review. NISTIR 8351-Draft.* 2021. doi: doi:10.6028/NIST.IR.8351-draft.

Open proficiency testing, where analysts know they are being tested, may artificially inflate impressions of accuracy compared with standard casework testing protocols.[592] Proficiency test items may not resemble casework items and generally enter workflows through different channels than casework, with different packaging, paperwork, and requests for analysis. Samples may be processed differently than casework, processed and interpreted by individuals rather than collaborative teams, worked on by personnel that rarely perform the task except for the sole purpose of maintaining an authorization in a technique, or subjected to additional levels of review and checking such as the inter-comparison of results from different individuals within the same proficiency testing round prior to submission and marking. For individual analysts, it is also possible that the knowledge of being tested causes conscious or subconscious changes in behavior and decision-making compared with casework.[593]

Furthermore, many proficiency tests use the same samples for multiple participants, including those within the same FSSP. This method may enable participants to compare results with each other before submission, thus artificially inflating the accuracy. To prevent this, it is preferable that test providers administer a different test or tests with randomized samples to each analyst in the FSSP, thus preventing collaboration and pre-submission error correction.

8.8.1 Blind Proficiency Testing

The 2009 National Academy of Sciences (NAS) Report and the 2016 President's Council of Advisors on Science and Technology (PCAST) Report recommend blind proficiency testing as the preferential method of system-based performance testing for the forensic sciences.[594] This is the ideal method of effective performance testing because it provides a more precise assessment of end-to-end system performance, including sample acceptance, item handling, selection of techniques, and correct use of SOPs relative to the requested testing and nature of reporting. Importantly, blind testing provides the ability for FSSPs to assess decision-making and expertise.

In blind testing, analysts are unaware that the item or case they are working on is a test using known items. Test providers package and submit samples that resemble evidence items to FSSPs in alignment with that FSSP's normal procedures. These samples are then processed by analysts unaware they are not processing a real case. Although overall accuracy may be similar for some

[592] Hundl C, Neuman M, Rairden A, Rearden P, Stout P. Implementation of a Blind Quality Control Program in a Forensic Laboratory. *Journal of Forensic Sciences*. 2020; 65(3):815-22. doi:10.1111/1556-4029.14259.

[593] Orne MT. On the Social Psychology of the Psychological Experiment: With Particular Reference to Demand Characteristics and Their Implications. *American Psychologist*. 1962; 17(11):776-83. doi:10.1037/h0043424.

[594] National Research Council, Committee on Identifying the Needs of the Forensic Science Community. *Strengthening Forensic Science in the United States: A Path Forward*. The National Academies Press: Washington, DC, 2009. doi:10.21428/cb6ab371.b2d683d2; President's Council of Advisors on Science and Technology (PCAST). *Report to the President: Forensic Science in Criminal Courts: Ensuring Scientific Validity of Feature-Comparison Methods*. 2016.
https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/PCAST/pcast_forensic_science_report_final.pdf.

disciplines between open and blind proficiency tests,[595] root cause analysis of blind testing in one FSSP found nonconformities in areas involving subjective interpretation more frequently in blind testing than in open testing.[596]

In addition to providing realistic assessments of FSSP performance, Hundl et al.[597] noted that blind testing may capitalize on the Hawthorne effect,[598] whereby the knowledge of being observed modifies behavior. In the case of declared blind testing programs, analysts may never know which case could be a test and, as such, may be more conscious of complying with SOPs and making careful decisions in every case.

An early feasibility study in blind proficiency testing for DNA found that a national approach would be costly and complex to implement and administer successfully.[599] Despite these difficulties, several FSSPs have implemented internal blind testing programs across multiple disciplines, with one FSSP finding that the costs are minimal compared with the cost of traditional open tests.[600]

There is an increased cost in time and labor for personnel involved in the construction and administration of tests. For example, the Houston Forensic Science Center (HFSC) estimates that it requires two full-time personnel members within their Quality Division to oversee and administer their program of approximately 300 samples per year across six disciplines.[601] Logistically, some FSSPs may experience obstacles to the full introduction of blind proficiency testing in terms of assigning case numbers, entry to LIMS, multidisciplinary evidence recovery, or reporting to external agencies. However, FSSPs such as HFSC demonstrate that these obstacles may be overcome with time, resourcing, and commitment.

Due to legal restrictions on the use of local, national, or international databases, there are additional challenges to implementing blind proficiency tests in forensic biology. FSSPs may be prevented from searching or uploading volunteer samples to databases, the use of personnel samples to construct tests may result in the detection of tests through elimination databases,

[595] Hundl C, Neuman M, Rairden A, Rearden P, Stout P. Implementation of a Blind Quality Control Program in a Forensic Laboratory. *Journal of Forensic Sciences*. 2020; 65(3):815-22. doi:10.1111/1556-4029.14259.

[596] Pierce ML, Cook LJ. Development and Implementation of an Effective Blind Proficiency Testing Program. *Journal of Forensic Sciences*. 2020; 65(3):809-14. doi:10.1111/1556-4029.14269.

[597] Hundl C, Neuman M, Rairden A, Rearden P, Stout P. Implementation of a Blind Quality Control Program in a Forensic Laboratory. *Journal of Forensic Sciences*. 2020; 65(3):815-22. doi:10.1111/1556-4029.14259.

[598] Parsons HM. What Happened at Hawthorne?: New Evidence Suggests the Hawthorne Effect Resulted from Operant Reinforcement Contingencies. *Science*. 1974; 183(4128):922-32. doi:10.1126/science.183.4128.922.

[599] Peterson JL, Gaensslen RE. *Developing Criteria for Model External DNA Proficiency Testing, Final Report*. U.S. Department of Justice Office of Justice Programs. 2001. https://www.ojp.gov/library/publications/developing-criteria-model-external-dna-proficiency-testing-final-report.

[600] Hundl C, Neuman M, Rairden A, Rearden P, Stout P. Implementation of a Blind Quality Control Program in a Forensic Laboratory. *Journal of Forensic Sciences*. 2020; 65(3):815-22. doi:10.1111/1556-4029.14259.

[601] Ibid.

and the repeated use of the same donors may provide an opportunity for detection through familiarity.

Current blind testing programs in forensic biology are restricted to testing processes up until database entry, with test samples detected through elimination database searches or intervention from an FSSP manager aware of the test.[602] However, to allow blind proficiency tests to be effective assessments of the entire workflow, restrictions on the use of databases for QA/QC and testing will need to be removed or reduced. FSSPs may also be required to ensure that samples uploaded for test purposes are identifiable and removable following test completion.

8.9 Provision of Practice and Feedback Opportunities for Expertise Development

Limitations of current proficiency tests mean that such tests cannot be used to demonstrate or enhance the full range of an analyst's *competency* within a specific skill. To do so, it would be necessary for proficiency tests to explore the full range of sample types of possible responses (including inconclusive or uninterpretable responses). Although possible, multi-FSSP tests of this nature are difficult to design because of the wide range of systems in use across the field. Assessment is also considerably more challenging because of the higher probability of inconclusive, nonreportable, or uninformative results.

Within complex systems that involve human judgments, it is important to provide regular opportunities for practicing a task, obtaining feedback on performance, and making errors that can be treated as learning opportunities. Numerous fields have shown that expertise does not develop or increase if a skill is not regularly practiced and no feedback on performance is received.[603] In the absence of feedback, experience performing a task does not guarantee skill maintenance, particularly when most of the work is performed without the ground-truth-known.[604]

In forensic science, most feedback is obtained during training—either during the initial employment period or through introduction of new systems and methods. Because ground-truth is not known, casework and case outcomes are not an appropriate substitute for feedback on

[602] Ibid.

[603] Ericsson K, Charness, N., Feltovich, P., & Hoffman, R. *The Cambridge Handbook of Expertise and Expert Performance*. Cambridge University Press: New York, NY, 2006. doi:10.1017/CBO9780511816796.

[604] Edmond G, Towler A, Growns B, Ribeiro G, Found B, White D, Ballantyne KN, Searston RA, Thompson MB, Tangen JM, Kemp RI, Martire K. Thinking Forensics: Cognitive Science for Forensic Practitioners. *Science & Justice*. 2017; 57(2):144-154. doi:10.1016/j.scijus.2016.11.005.

ground-truth samples.[605] However, this may mean that analysts can use techniques for many years without obtaining feedback. In such cases, although expertise may not diminish, it is unlikely to increase without feedback.

Studies in forensic disciplines have shown no link between experience and accuracy.[606] Researchers have found no correlation between accuracy and years of experience for trained and authorized document examiners,[607] fingerprint examiners,[608] or facial identification experts.[609] Edmond et al. attribute this finding to a lack of regular, timely, and appropriate feedback from continuous training and practice.[610]

A lack of increase in expertise could be problematic in court settings, given that end-users place more weight on evidence from highly experienced practitioners than identical evidence from less-experienced colleagues.[611] Furthermore, more senior personnel may be given more complex cases and tasks to perform or review. It may also be common for disagreements of opinion to be mediated by more experienced practitioners, with deference to their perceived increased expertise. However, the EWG is not aware of any existing data within any discipline of forensic science to support the claim that increased experience results in increased expertise.

When provided in a timely manner, feedback can allow analysts to develop and expand their skills, reflect on performance, and adjust and calibrate decision thresholds or knowledge bases to improve their expertise.[612] Therefore, DNA analysts should regularly practice their skills and

[605] President's Council of Advisors on Science and Technology (PCAST). *Report to the President: Forensic Science in Criminal Courts: Ensuring Scientific Validity of Feature-Comparison Methods*. 2016. https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/PCAST/pcast_forensic_science_report_final.pdf.

[606] Baldwin DP, Bajic SJ, Morris M, Zamzow D. *A Study of False-Positive and False-Negative Error Rates in Cartridge Case Comparisons*. Ames Laboratory, USDOE. 2014. https://www.ojp.gov/pdffiles1/nij/249874.pdf; Hicklin RA, Winer KR, Kish PE, Parks CL, Chapman W, Dunagan K, Richetelli N, Epstein EG, Ausdemore MA, Busey TA. Accuracy and Reproducibility of Conclusions by Forensic Bloodstain Pattern Analysts. *Forensic Science International*. 2021; 325:110856. doi:10.1016/j.forsciint.2021.110856; Sita J, Found B, Rogers DK. Forensic Handwriting Examiners' Expertise for Signature Comparison. *Journal of Forensic Sciences*. 2002; 47(5):1117-24. doi:10.1520/jfs15521j; Ulery BT, Hicklin RA, Buscaglia J, Roberts MA. Accuracy and Reliability of Forensic Latent Fingerprint Decisions. *Proceedings of the National Academy of Sciences of the United States of America*. 2011; 108(19):7733-8. doi:10.1073/pnas.1018707108.

[607] Sita J, Found B, Rogers DK. Forensic Handwriting Examiners' Expertise for Signature Comparison. *Journal of Forensic Sciences*. 2002; 47(5):1117-24. doi:10.1520/jfs15521j.

[608] Ulery BT, Hicklin RA, Buscaglia J, Roberts MA. Accuracy and Reliability of Forensic Latent Fingerprint Decisions. *Proceedings of the National Academy of Sciences of the United States of America*. 2011; 108(19):7733-8. doi:10.1073/pnas.1018707108.

[609] White D, Kemp RI, Jenkins R, Matheson M, Burton AM. Passport Officers' Errors in Face Matching. *PloS One*. 2014; 9(8):e103510. doi:10.1371/journal.pone.0103510.

[610] Edmond G, Towler A, Growns B, Ribeiro G, Found B, White D, Ballantyne KN, Searston RA, Thompson MB, Tangen JM, Kemp RI, Martire K. Thinking Forensics: Cognitive Science for Forensic Practitioners. *Science & Justice*. 2017; 57(2):144-154. doi:10.1016/j.scijus.2016.11.005.

[611] Koehler JJ, Schweitzer NJ, Saks MJ, McQuiston DE. Science, Technology, or the Expert Witness: What Influences Jurors' Judgments About Forensic Science Testimony? *Psychology, Public Policy, and Law*. 2016; 22(4):401-13. doi:10.1037/law0000103; McCarthy Wilcox A, NicDaeid N. Jurors' Perceptions of Forensic Science Expert Witnesses: Experience, Qualifications, Testimony Style and Credibility. *Forensic Science International*. 2018; 291:100-8. doi:10.1016/j.forsciint.2018.07.030.

[612] Ericsson K, Charness, N., Feltovich, P., & Hoffman, R. *The Cambridge Handbook of Expertise and Expert Performance*. Cambridge University Press: New York, NY, 2006. doi:10.1017/CBO9780511816796.

obtain feedback on the accuracy, reliability, and reproducibility of their judgments relative to ground-truth or, in cases where there may not be objective ground-truth, to their peers.

Since it is known that knowledge, skills, and abilities (KSAs) are task-specific and generally nontransferable, the relatively rapid rate of change in DNA profiling compared to other forensic disciplines may also further reduce any link between experience and expertise.[613] Thus, experience in manual profile interpretation and comparison may not have any impact on ability to assess profiles for probabilistic genotyping, activity-level assessments, or serology. As such, DNA analysts and criminal justice partners should not make assumptions regarding expert ability and experience and should not use experience in a task as a proxy for accuracy, knowledge, or superior performance.

8.9.1 Training Exercises to Maintain and Increase Expertise

The provision of regular ground-truth-known exercises is a mechanism to give DNA analysts the necessary practice and feedback to increase their expertise. Training exercises, which allow an analyst to build skill and develop expertise, are routinely used during the initial period of learning but in many FSSPs are not regularly provided after authorization.

Unlike proficiency tests, which are formally administered, may be performed by a group of individuals across the entire process, and in which errors have serious consequences, training exercises should be individually performed and may test only part of the process or even a single decision. Training exercises in forensic biology may involve providing DNA profiles to analysts for NOC determination, posing scenarios to analysts to test the identification of variables that may affect DNA deposition or transfer, or using standard sets of slides to test sperm identification between analysts.

Depending on the stimuli and skill involved, training exercises may be reused between multiple analysts, administered to multiple analysts simultaneously to indicate inter-analyst reproducibility, or administered to the same analyst at different times to give intra-analyst reliability. They do not need to test the entire workflow but can focus on sections or even individual decisions. As such, there may be fewer resources required to produce and administer training exercises than those needed for proficiency tests, both in terms of material costs and analyst time.

Although ongoing exercises could be combined with proficiency testing programs—particularly if such tests are diversified and made more representative of casework—there are specific advantages to having separate programs. Proficiency testing can be used to demonstrate the

[613] Ericsson KA, Lehmann AC. Expert and Exceptional Performance: Evidence of Maximal Adaptation to Task Constraints. *Annual Review of Psychology*. 1996; 47:273-305. doi:10.1146/annurev.psych.47.1.273.

ability of the *system* to achieve accurate results, while training exercises can be used to demonstrate the ability of the *individual* to operate at the edges of where the system is designed to operate. In this regard, an important differentiation should be made—ongoing training should encourage or allow errors to enable a growth in knowledge and skills.

As the focus of ongoing skill testing (outside of end-of-training competency or authorization testing) is on maintaining and building expertise, it is important that the tests involve the full range of difficulties and decisions that an analyst may be exposed to in casework. Testing inconclusive or uninformative decision thresholds can help an analyst identify when the limits of a technique are reached or when an analyst may be displaying inappropriate levels of conservatism or confidence. Ongoing testing may also include a verbal assessment, ensuring that the analyst continues to effectively communicate relevant information during testimony.

Providing regular practice and feedback may be particularly important when methods or procedures change frequently because of software changes or when there are increases in knowledge about the behavior of systems. Designing highly challenging exercises, where mistakes may occur more frequently than in routine proficiency tests, can be a valuable way of overcoming aversion to error and provide analysts with experience in identifying situations with a higher risk of error.

Examples of such exercises include DNA samples containing multiple related contributors for NOC estimation and profile comparison or serological testing of biological material that has been subjected to cleaning fluids and therefore provides a false negative result. As noted by the National Commission on Forensic Science (NCFS) in relation to performance testing, a low rate of failure within and across testing rounds indicates the inadequacy of tests, while frequent failure is the hallmark of a rigorous performance system.[614]

At the time of this report, there is insufficient evidence for the required frequency of practice/testing to build initial competence, grow abilities after authorization, or maintain expertise over time. It may be linked to the complexity of the task at hand and the decision-making required; a simple task that can be performed with relative ease may only require a yearly exercise. A difficult, high-risk task that requires high levels of skill and knowledge may need monthly exercises, at least until a strong base is developed. Further research on the development and maintenance of expertise in DNA analysis is required, but there is no evidence to suggest that the overarching framework of practice and feedback established in other domains would not apply to forensic science, generally, and DNA, specifically.

[614] National Commission on Forensic Science. *Views of the Commission: Optimizing Human Performance in Crime Laboratories through Testing and Feedback*. 2016. https://www.justice.gov/archives/ncfs/page/file/864776/download.

It is important to recognize that if exercises are designed to be challenging and induce error, the results should not be used to infer the analyst's performance rates on routine casework tasks. Therefore, it is important that performance feedback is given in a constructive, nonpunitive manner and that errors on exercises designed to specifically induce such errors are not subjected to corrective actions or performance management. They should be treated as learning opportunities.

FSSPs should implement monitoring of skill-based exercise results over time and have procedures to address instances when analysts are routinely committing errors on challenging exercises. If training exercises are not improving performance, it is important to understand why not so that errors can be reduced in casework. FSSPs should increase training, practice, and feedback opportunities for the analyst rather than take actions that create a culture of error aversion through other punitive actions.

The inherent nature of challenging exercises means that data on results should not be used by criminal justice partners to infer overall analyst performance in casework, unless presented carefully and with due regard for the nature and purpose of the exercises. Particularly for challenging exercises focusing only on part of the process, equating exercise error rates to overall process error rates on standard or simple samples would be misleading and would severely misrepresent the *average* performance of the analyst across the entire range of difficulties experienced in casework.

Although FSSPs may be required to disclose results of all types of performance testing, NCFS urged courts to give careful consideration to the admittance of such evidence, recommending that it only occurs in narrow circumstances and with careful explanations of the limitations of the data for establishing the overall probability of error within the case.[615] In instances when disclosure of training exercise results is required by the court, NCFS has recommended that the results are accompanied by documents explaining the nature, extent, and purpose of the testing regime, along with how closely the test design resembles tasks performed in casework by the analyst.

The EWG supports the NCFS recommendation and, when the results of training exercises and competency tests are relevant and requested, encourages criminal justice partners to consider the results in the context of the testing purpose and nature. We further recommend providing information to assist the courts in this consideration when the results of training exercises and competency tests are requested.

[615] Ibid.

This publication is available free of charge from: https://doi.org/10.6028/NIST.IR.8503

It will be critical for FSSPs to explain to criminal justice partners that, although sometimes relevant, training exercises are designed to stimulate reflective practice and learning, and as such, they do not necessarily fully reflect competency under casework circumstances. Although some exercises may come with "satisfactory" performance thresholds, for other exercises without ground-truth it may not be possible to define an absolute threshold for competence. Therefore, the results should be interpreted considering their purpose—building and maintaining expertise.

Recommendation 8.5: To regularly monitor performance, forensic science service providers should assess both system and individual performance through internal or external testing regimes that reflect the range of complexity encountered and the procedures used in casework.

Recommendation 8.6: Forensic science service providers should provide analysts with training exercises at intervals related to task complexity. These exercises should comprise a variety of difficult, error-prone, and uninterpretable samples, in which analysts receive feedback in a nonpunitive training environment to further develop and maintain their expertise.

8.9.2 Collaborative Trials

One common way to perform competency testing and benchmarking is through collaborative or inter-laboratory trials. In these trials, participating FSSPs receive highly similar or identical materials, perform specific analyses, and return their results to the organizing FSSP for collation, analysis, and reporting. As such, trials are not tied to accreditation requirements but are used as benchmarking exercises.

Any FSSP can organize and disseminate the collaborative trials; participants may use any means of processing, interpreting, and reporting that align with their SOPs. Collaborative trials in forensic biology have been conducted on mitochondrial DNA (mtDNA) profiling, Y-chromosome short tandem repeat (Y-STR) profiling, autosomal DNA profiling, mixture analysis and interpretation, messenger ribonucleic acid (mRNA) testing, and DNA phenotyping.[616]

[616] Bright JA, Cheng K, Kerr Z, McGovern C, Kelly H, Moretti TR, Smith MA, Bieber FR, Budowle B, Coble MD, Alghafri R, Allen PS, Barber A, Beamer V, Buettner C, Russell M, Gehrig C, Hicks T, Charak J, Cheong-Wing K, Ciecko A, Davis CT, Donley M, Pedersen N, Gartside B, Granger D, Greer-Ritzheimer M, Reisinger E, Kennedy J, Grammer E, Kaplan M, Hansen D, Larsen HJ, Laureano A, Li C, Lien E, Lindberg E, Kelly C, Mallinder B, Malsom S, Yacovone-Margetts A, McWhorter A, Prajapati SM, Powell T, Shutler G, Stevenson K, Stonehouse AR, Smith L, Murakami J, Halsing E, Wright D, Clark L, Taylor DA, Buckleton J. STRmix™ Collaborative Exercise on DNA Mixture Interpretation. *Forensic Science International: Genetics*. 2019; 40:1-8. doi:10.1016/j.fsigen.2019.01.006; Buckleton J, Bright JA, Cheng K, Budowle B, Coble MD. NIST Interlaboratory Studies Involving DNA Mixtures (MIX13): A Modern Analysis. *Forensic Science International: Genetics*. 2018; 37:172-179. doi:10.1016/j.fsigen.2018.08.014; Carracedo A, Beckmann A, Bengs A, Brinkmann B, Caglia A, Capelli C, Gill P, Gusmao L, Hagelberg C, Hohoff C, Hoste B, Kihlgren A, Kloosterman A, Myhre Dupuy B, Morling N, O'Donnell G, Parson W, Phillips C, Pouwels M, Scheithauer R, Schmitter H,

Collaborative trials have demonstrated, for example, variation in mixture interpretation, LRs, and reporting style and format;[617] the impact of training on inter-laboratory consistency;[618] and the repeatability of particular methods on the same samples between FSSPs.[619] Published studies

Schneider PM, Schumm J, Skitsa I, Stradmann-Bellinghausen B, Stuart M, Syndercombe Court D, Vide C. Results of a Collaborative Study of the EDNAP Group Regarding the Reproducibility and Robustness of the Y-Chromosome STRs DYS19, DYS389 I and II, DYS390 and DYS393 in a PCR Pentaplex Format. *Forensic Science International*. 2001; 119(1):28-41. doi:10.1016/s0379-0738(00)00395-9; Chaitanya L, Walsh S, Andersen JD, Ansell R, Ballantyne KN, Ballard D, Banemann R, Bauer CM, Bento AM, Brisighelli F, Capal T, Clarisse L, Gross TE, Haas C, Hoff-Olsen P, Hollard C, Keyser C, Kiesler KM, Kohler P, Kupiec T, Linacre A, Minawi A, Morling N, Nilsson H, Noren L, Ottens R, Palo JU, Parson W, Pascali VL, Phillips C, Porto MJ, Sajantila A, Schneider PM, Sijen T, Sochtig J, Syndercombe-Court D, Tillmar A, Turanska M, Vallone PM, Zatkalikova L, Zidkova A, Branicki W, Kayser M. Collaborative EDNAP Exercise on the IrisPlex System for DNA-Based Prediction of Human Eye Colour. *Forensic Science International: Genetics*. 2014; 11:241-51. doi:10.1016/j.fsigen.2014.04.006; Crespillo M, Barrio PA, Luque JA, Alves C, Aler M, Alessandrini F, Andrade L, Barretto RM, Bofarull A, Costa S, Garcia MA, Garcia O, Gaviria A, Gladys A, Gorostiza A, Hernandez A, Pinero MH, Hombreiro L, Ibarra AA, Jimenez MJ, Luque GM, Madero P, Martinez-Jarreta B, Masciovecchio MV, Modesti NM, Moreno F, Pagano S, Pedrosa S, Plaza G, Prat E, Puente J, Rendo F, Ribeiro T, Sala A, Santamaria E, Saragoni VG, Whittle MR. GHEP-ISFG Collaborative Exercise on Mixture Profiles of Autosomal STRs (GHEP-MIX01, GHEP-MIX02 and GHEP-MIX03): Results and Evaluation. *Forensic Science International: Genetics*. 2014; 10:64-72. doi:10.1016/j.fsigen.2014.01.009; Haas C, Hanson E, Anjos MJ, Ballantyne KN, Banemann R, Bhoelai B, Borges E, Carvalho M, Courts C, De Cock G, Drobnic K, Dotsch M, Fleming R, Franchi C, Gomes I, Hadzic G, Harbison SA, Harteveld J, Hjort B, Hollard C, Hoff-Olsen P, Huls C, Keyser C, Maronas O, McCallum N, Moore D, Morling N, Niederstatter H, Noel F, Parson W, Phillips C, Popielarz C, Roeder AD, Salvaderi L, Sauer E, Schneider PM, Shanthan G, Court DS, Turanska M, van Oorschot RA, Vennemann M, Vidaki A, Zatkalikova L, Ballantyne J. RNA/DNA Co-Analysis from Human Menstrual Blood and Vaginal Secretion Stains: Results of a Fourth and Fifth Collaborative EDNAP Exercise. *Forensic Science International: Genetics*. 2014; 8(1):203-12. doi:10.1016/j.fsigen.2013.09.009; Parson W, Brandstätter A, Alonso A, Brandt N, Brinkmann B, Carracedo A, Corach D, Froment O, Furac I, Grzybowski T, Hedberg K, Keyser-Tracqui C, Kupiec T, Lutz-Bonengel S, Mevag B, Ploski R, Schmitter H, Schneider P, Syndercombe-Court D, Sorensen E, Thew H, Tully G, Scheithauer R. The EDNAP Mitochondrial DNA Population Database (EMPOP) Collaborative Exercises: Organisation, Results and Perspectives. *Forensic Science International*. 2004; 139(2-3):215-26. doi:10.1016/j.forsciint.2003.11.008; Prieto L, Haned H, Mosquera A, Crespillo M, Aleman M, Aler M, Alvarez F, Baeza-Richer C, Dominguez A, Doutremepuich C, Farfan MJ, Fenger-Gron M, Garcia-Ganivet JM, Gonzalez-Moya E, Hombreiro L, Lareu MV, Martinez-Jarreta B, Merigioli S, Milans Del Bosch P, Morling N, Munoz-Nieto M, Ortega-Gonzalez E, Pedrosa S, Perez R, Solis C, Yurrebaso I, Gill P. Euroforgen-NoE Collaborative Exercise on LRmix to Demonstrate Standardization of the Interpretation of Complex DNA Profiles. *Forensic Science International: Genetics*. 2014; 9:47-54. doi:10.1016/j.fsigen.2013.10.011; Robino C, Ralf A, Pasino S, De Marchi MR, Ballantyne KN, Barbaro A, Bini C, Carnevali E, Casarino L, Di Gaetano C, Fabbri M, Ferri G, Giardina E, Gonzalez A, Matullo G, Nutini AL, Onofri V, Piccinini A, Piglionica M, Ponzano E, Previdere C, Resta N, Scarnicci F, Seidita G, Sorcaburu-Cigliero S, Turrina S, Verzeletti A, Kayser M. Development of an Italian RM Y-STR Haplotype Database: Results of the 2013 GEFI Collaborative Exercise. *Forensic Science International: Genetics*. 2015; 15:56-63. doi:10.1016/j.fsigen.2014.10.008; Toscanini U, Gusmão L, Álava Nárvaez MC, Alvarez JC, Baldassarri L, Barbaro A, Berardi G, Betancor Hernandez E, Camargo M, Carreras-Carbonell J, Castro J, Costa SC, Coufalova P, Dominguez V, Fagundes de Carvalho E, Ferreira STG, Furfuro S, Garcia O, Goios A, Gonzalez R, de la Vega AG, Gorostiza A, Hernandez A, Jimenez Moreno S, Lareu MV, Leon Almagro A, Marino M, Martinez G, Miozzo MC, Modesti NM, Onofri V, Pagano S, Pardo Arias B, Pedrosa S, Penacino GA, Pontes ML, Porto MJ, Puente-Prieto J, Perez RR, Ribeiro T, Rodriguez Cardozo B, Rodriguez Lesmes YM, Sala A, Santiago B, Saragoni VG, Serrano A, Streitenberger ER, Torres Morales MA, Vannelli Rey SA, Velazquez Miranda M, Whittle MR, Fernandez K, Salas A. Analysis of Uni and Bi-Parental Markers in Mixture Samples: Lessons from the 22nd GHEP-ISFG Intercomparison Exercise. *Forensic Science International: Genetics*. 2016; 25:63-72. doi:10.1016/j.fsigen.2016.07.010; van den Berge M, Carracedo A, Gomes I, Graham EAM, Haas C, Hjort B, Hoff-Olsen P, Maronas O, Mevag B, Morling N, Niederstatter H, Parson W, Schneider PM, Court DS, Vidaki A, Sijen T. A Collaborative European Exercise on mRNA-Based Body Fluid/Skin Typing and Interpretation of DNA and RNA Results. *Forensic Science International: Genetics*. 2014; 10:40-8. doi:10.1016/j.fsigen.2014.01.006.

[617] Barrio PA, Crespillo M, Luque JA, Aler M, Baeza-Richer C, Baldassarri L, Carnevali E, Coufalova P, Flores I, Garcia O, Garcia MA, Gonzalez R, Hernandez A, Ingles V, Luque GM, Mosquera-Miguel A, Pedrosa S, Pontes ML, Porto MJ, Posada Y, Ramella MI, Ribeiro T, Riego E, Sala A, Saragoni VG, Serrano A, Vannelli S. GHEP-ISFG Collaborative Exercise on Mixture Profiles (GHEP-MIX06). Reporting Conclusions: Results and Evaluation. *Forensic Science International: Genetics*. 2018; 35:156-163. doi:10.1016/j.fsigen.2018.05.005; Benschop CCG, Connolly E, Ansell R, Kokshoorn B. Results of an Inter and Intra Laboratory Exercise on the Assessment of Complex Autosomal DNA Profiles. *Science & Justice*. 2017; 57(1):21-7. doi:10.1016/j.scijus.2016.10.001; Butler JM, Kline MC, Coble MD. NIST Interlaboratory Studies Involving DNA Mixtures (MIX05 and MIX13): Variation Observed and Lessons Learned. *Forensic Science International: Genetics*. 2018; 37:81-94. doi:10.1016/j.fsigen.2018.07.024.

[618] Prieto L, Haned H, Mosquera A, Crespillo M, Aleman M, Aler M, Alvarez F, Baeza-Richer C, Dominguez A, Doutremepuich C, Farfan MJ, Fenger-Gron M, Garcia-Ganivet JM, Gonzalez-Moya E, Hombreiro L, Lareu MV, Martinez-Jarreta B, Merigioli S, Milans Del Bosch P, Morling N, Munoz-Nieto M, Ortega-Gonzalez E, Pedrosa S, Perez R, Solis C, Yurrebaso I, Gill P. Euroforgen-NoE Collaborative Exercise on LRmix to Demonstrate Standardization of the Interpretation of Complex DNA Profiles. *Forensic Science International: Genetics*. 2014; 9:47-54. doi:10.1016/j.fsigen.2013.10.011.

[619] Carracedo A, Beckmann A, Bengs A, Brinkmann B, Caglia A, Capelli C, Gill P, Gusmao L, Hagelberg C, Hohoff C, Hoste B, Kihlgren A, Kloosterman A, Myhre Dupuy B, Morling N, O'Donnell G, Parson W, Phillips C, Pouwels M, Scheithauer R, Schmitter H, Schneider PM, Schumm J, Skitsa I, Stradmann-Bellinghausen B, Stuart M, Syndercombe Court D, Vide C. Results of a Collaborative Study of the EDNAP Group Regarding the Reproducibility and Robustness of the Y-Chromosome STRs DYS19, DYS389 I and II, DYS390 and DYS393 in a PCR Pentaplex Format. *Forensic Science International*. 2001; 119(1):28-41. doi:10.1016/s0379-0738(00)00395-9; Toscanini U, Gusmão L, Álava Nárvaez MC, Alvarez JC, Baldassarri L, Barbaro A, Berardi G, Betancor Hernandez E, Camargo M, Carreras-Carbonell J, Castro J, Costa SC, Coufalova P, Dominguez V,

have largely focused on the comparison between FSSPs, but the collaborative trial model could be used to test the competency, accuracy, or reproducibility of individual analysts and their decisions, depending on the task at hand.

This model has been successfully employed in other forensic science domains, most notably for the examination of handwriting and signatures, with large collaborative trials running across multiple years providing more than 45,000 blind opinions on signatures and 30,000 on handwritten text.[620] Useful data gleaned from these trials include worldwide error rates; information on the adequacy of training and effectiveness of quality systems; and, for participants, personalized knowledge about their performance across different types of tasks. These trials allowed for reflection on mistakes made, revision of performance and decision-making, and correction of methodology to improve accuracy.

Within forensic DNA, collaborative trials could be used in a similar manner to provide competency and decision-making feedback to FSSPs. Trials involving critical tasks and decisions could be performed as benchtop exercises, using appropriately challenging DNA profiles to test NOC determinations, suitability for probabilistic genotyping, or allelic designations. In addition, FSSPs could use scenario-based exercises that do not involve laboratory work or DNA profiles to test the development of propositions and examination strategies.

Collaborative trials have the benefit of reducing the workload on any individual FSSP, particularly where the responsibility for design, administration, and analysis of different trials is shared between agencies. Although inter-laboratory differences in processing methodology, thresholds, software, and interpretation criteria may increase the complexity in constructing and interpreting some trial results, previous trials have demonstrated that these difficulties can be overcome. In addition to providing valuable inter-analyst comparisons within FSSPs, such trials would enable national benchmarking between FSSPs.

8.10 Nonconformity Detection and Prevention

ISO defines *nonconforming work* as "any aspect of its laboratory activities or results of this work [that does not] conform to its own procedures or the agreed requirements of the customer."[621]

Fagundes de Carvalho E, Ferreira STG, Furfuro S, Garcia O, Goios A, Gonzalez R, de la Vega AG, Gorostiza A, Hernandez A, Jimenez Moreno S, Lareu MV, Leon Almagro A, Marino M, Martinez G, Miozzo MC, Modesti NM, Onofri V, Pagano S, Pardo Arias B, Pedrosa S, Penacino GA, Pontes ML, Porto MJ, Puente-Prieto J, Perez RR, Ribeiro T, Rodriguez Cardozo B, Rodriguez Lesmes YM, Sala A, Santiago B, Saragoni VG, Serrano A, Streitenberger ER, Torres Morales MA, Vannelli Rey SA, Velazquez Miranda M, Whittle MR, Fernandez K, Salas A. Analysis of Uni and Bi-Parental Markers in Mixture Samples: Lessons from the 22nd GHEP-ISFG Intercomparison Exercise. *Forensic Science International: Genetics*. 2016; 25:63-72. doi:10.1016/j.fsigen.2016.07.010.

[620] Found B, Rogers D. The Probative Character of Forensic Handwriting Examiners' Identification and Elimination Opinions on Questioned Signatures. *Forensic Science International*. 2008; 178(1):54-60. doi:10.1016/j.forsciint.2008.02.001.

[621] International Organization for Standardization (ISO). *General Requirements for the Competence of Testing and Calibration Laboratories, ISO/IEC 17025:2017*. 2017. https://www.iso.org/standard/66912.html. *See* 7.10.1

FSSPs should identify and address nonconformities to ensure their potential impact to casework is appropriately evaluated.

Depending on the severity of a nonconformity, the incident may be documented for informational purposes, or a corrective action may be required to prevent it from recurring (see ***Sec. 8.10.2*: *Corrective Actions***). This decision should be based on the probability of the nonconformity reoccurring and its potential impact on casework, as determined by a risk analysis.

8.10.1 Risk Analysis

To determine what action should be taken to address a nonconformity, FSSPs should use a risk-based approach, such as risk analysis. Risk analysis is the process of identifying, categorizing, and analyzing nonconformities that impact the DNA analysis process. The FSSP can perform a risk analysis preemptively or retroactively. Using this method requires an effective procedure, including five elements: "preparation, identification, analysis/evaluation, control, and review."[622]

ISO/IEC 31000:2018[623] explains the risk management process in detail. Generally, an FSSP should first identify the resources and personnel that will be allocated to this process and then evaluate all aspects of its operations to identify risks that could hinder the process from fulfilling its objectives. Having determined the risks, or if a nonconformity has already occurred, the FSSP should then perform an analysis to understand the nature of the nonconformity, including the level of risk. In addition to other elements, this analysis should consider the likelihood of the event, the consequence if the event occurs, and what controls are present to help detect the event. The risk analysis can then be compared to the established risk criteria to determine if any action is required.

The established risk criteria may be represented in a risk matrix, which is a table that visualizes the factors that were considered in the risk analysis (see **Fig. 8.1**). Typically, one side of the table will contain a range of probabilities/frequencies and the other side will have a range of impacts/severities. Alternatively, different categories (e.g., classes, levels, types) of risk may be defined based on specific combinations of the established risk criteria (e.g., Type I error, Type II error). The last step involves monitoring the outcome of the action to determine if it was effective in minimizing the risk. Although the general process is linear, any step can be repeated as needed.

[622] Dror IE, Pierce ML. ISO Standards Addressing Issues of Bias and Impartiality in Forensic Work. *Journal of Forensic Sciences*. 2020; 65(3):800-8. doi:10.1111/1556-4029.14265.

[623] International Organization for Standardization (ISO). *Risk Management Guidelines, ISO/IEC 31000:2018*. 2018. https://www.iso.org/standard/65694.html.

Impact						
	5 – critical					
	4 – major					
	3 – moderate					
	2 – minor					
	1 - none					
		1 – remote	2 – unlikely	3 – somewhat likely	4 – likely	5 - frequent
		Probability of Recurrence				
	Corrective Action Report (CAR) will be initiated					
	CAR may be initiated or will be closely monitored; Preventative Action Report (PAR) may be initiated					
	A CAR or PAR may be initiated at any time at the discretion of the Quality Director or Deputy Director					

Levels of Impact Definitions	
None	No impact on evidence or casework, and therefore no impact to the customer
Minor	Insignificant impact on evidence or casework; potential impact to the customer (minor error or non-conformance that may or may not require an amended report or notification)
Moderate	Moderate impact on evidence or casework; impact to the customer (error or non-conformance that typically requires an amended report or notification)
Major	Significant impact on evidence or casework; impact to the customer (significant error or non-conformance that requires an amended report or notification)
Critical	Critical impact on evidence or casework; impact to the customer – incorrect results or the potential for incorrect results that could lead to the wrong conclusion (critical error or non-conformance that requires an amended report or notification)

Probability of Recurring (if not Addressed) Definitions	
Remote	Conceivable but not likely to occur again
Unlikely	Isolated incident; one occurrence every 1 – 3 years
Somewhat likely	Somewhat likely to reoccur; approximately one occurrence every year
Likely	Likely to reoccur; multiple occurrences each year
Frequent	Very likely to reoccur; multiple occurrences each month

Figure 8.1: An example risk matrix used in casework to assist with determining the level of risk associated with a nonconformity.

Figure adapted from and approved for reproduction by the Colorado Bureau of Investigation.[624]

A risk matrix is not the perfect solution for determining which nonconformities require corrective action. As noted by Cox, the matrix does not guarantee that qualitatively useful information for identifying high or low risks will be obtained, and the matrix is not always better than deciding randomly.[625] For example, if there is a negative correlation between the two factors being considered (i.e., low-probability/high-consequence versus high-probability/low-consequence), one scenario may appear to be more high risk than the other, when that is not the truth.

[624] Colorado Bureau of Investigation Forensic Services. *Quality Incident Review* 2024. *QP 11 ISO 710, Revision 5: 3/21/2024.* https://cbifs.qualtraxcloud.com/ShowDocument.aspx?ID=6959.

[625] Cox LA. What's Wrong with Risk Matrices? *Risk Analysis*. 2008; 28(2):497-512. doi:10.1111/j.1539-6924.2008.01030.x.

To be most useful, a risk matrix should, at minimum, be able to differentiate clearly between very high and very low risks.[626] This should be possible in an FSSP, since in most instances, two risks are not being compared to each other but are rather being evaluated individually to determine the best way to address each risk.

Many FSSPs have implemented a risk-based approach for addressing nonconformities, as this method is required for laboratories that are accredited to ISO/IEC 17025; however, the application of this standard varies. Several FSSPs have identified categories of nonconformities, while others have chosen to use a risk matrix to assist with evaluating a nonconformity.[627] In contrast, some FSSPs have not described specific criteria but instead state that a nonconformity shall be evaluated to determine whether previous casework has been affected or future casework could be affected.[628]

8.10.2 Corrective Actions

Depending on the level of the nonconformity evaluated, corrective action(s) may be required. A corrective action is a step or set of steps that are taken to address a nonconformity and prevent it from recurring. The FSSP should have a written procedure for determining when a corrective action is necessary as informed by results that can be reached after performing a risk assessment and subsequently determining the cause(s) of the nonconformity.[629]

The FSSP should also have a written procedure detailing how a corrective action is developed, implemented, and monitored to determine its effectiveness. Additionally, the procedure should include considerations of who should be informed about the corrective action (e.g., FSSP personnel, the customer, the courts, an accrediting body, or other involved parties) and when these individuals or entities should be informed (see ***Sec. 2.6: The Duty to Correct or Report Errors and Adverse Events***).

Those individuals overseeing the QA/QC program should be cognizant of what disclosure requirements exist, including information related to Brady and Giglio disclosures in the United States.[630] As disclosure requirements differ substantially between jurisdictions, each FSSP should

[626] Ibid.

[627] Colorado Bureau of Investigation Forensic Services. *Quality Incident Review* 2024. *QP 11 ISO 710, Revision 5: 3/21/2024.* https://cbifs.qualtraxcloud.com/ShowDocument.aspx?ID=6959.

[628] Kansas City Missouri Police Department. Crime Lab. Accessed March 27, 2024. https://www.kcpd.org/crime/crime-lab/; Las Vegas Metropolitan Police Department Forensic Laboratory. *Biology/DNA Detail Quality Manual*. 2023. https://www.lvmpd.com/home/showpublisheddocument/5200/638387677587930000.

[629] Percarpio KB, Watts BV, Weeks WB. The Effectiveness of Root Cause Analysis: What Does the Literature Tell Us? *The Joint Commission Journal on Quality and Patient Safety*. 2008; 34(7):391-8. doi:10.1016/S1553-7250(08)34049-5; Robitaille D. *Root Cause Analysis: Basic Tools and Techniques*. Paton Professional: 2010. ; Williams PM. Techniques for Root Cause Analysis. *Baylor University Medical Center Proceedings*. 2001; 14(2):154-7. doi:10.1080/08998280.2001.11927753.

[630] United States Supreme Court. *Brady v. Maryland, 373 U.S. 83*. 1963. ; United States Supreme Court. *Giglio v. United States, 405 U.S. 150* 1972.

ensure that disclosure requirements for corrective actions are addressed in SOPs. This may include a requirement to retain records of an individual's involvement in corrective action reports for disclosure purposes (see ***Sec. 6.3*: Discovery and Disclosures**).

The corrective action should be nonpunitive, focusing on the action that caused the nonconformity rather than the analyst who performed that action. Creating a culture and process that focuses on the system rather than the individual encourages reporting of nonconformities, which can then be appropriately addressed (see ***Chapter 10*: Management**). If analysts fear they will be punished or terminated for making a mistake, nonconformities may go unreported; depending on the type of nonconformity, they may also go undetected by quality checks.

Creating this culture extends beyond the FSSP and is undeniably intertwined with the legal system and criminal justice partners. FSSPs should look for ways to promote the goals of the nonpunitive nature of the system and support analysts who are tasked with answering to nonconformities outside of the FSSP (e.g., during testimony).

Although this discussion focuses on nonconformities and corrective actions, it should be noted that a risk analysis may be used to identify potential nonconformities that could have, but have not yet, occurred. The risk associated with an FSSP practice can be evaluated to identify steps where a potential nonconformity could occur and how frequently it may occur. If the risk of the nonconformity is great enough, a preventive action may be enacted to prevent its occurrence.

Similarly, a risk-based approach should be used when determining whether an FSSP should perform a retroactive case review. This may be necessary when a nonconformity is identified. Its impact has the potential to extend beyond the instance being evaluated. The FSSP should have a written procedure and a set of criteria for determining when a case review will be initiated and to what extent it will be conducted (e.g., all cases for a particular analyst over a specific period, a sample of cases from each analyst).

Written procedures on when to initiate a case review and to what extent should include, at minimum, considerations of the nature of the nonconformity, the frequency of occurrence, the number of different analysts/technicians who had the same nonconformity, and the impact to casework. Using a risk matrix or other risk-based approach in this procedure can assist in determining the overall impact and risk to casework that a nonconformity poses and inform the decision being made. An entity outside of the FSSP may also decide that a retroactive case review is required.

8.10.3 Human Factors in Risk Analysis

Although using a risk-based approach can create a framework for evaluating nonconformities and determining what scenarios require a corrective action, there is still some subjectivity in this

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process. Even with defined matrix parameters (e.g., impact and frequency of the occurrence), different evaluators of a nonconformity (e.g., the TL or quality manager) may demonstrate variability in opinion. For example, one evaluator may see a nonconformity as having a large impact, but another may see it as having a small impact.

An evaluator's opinion may also vary from day to day and be impacted by knowing who caused the nonconformity. As noted in ISO/IEC 31000:2018, a risk analysis "may be influenced by any divergence of opinions, biases, perceptions of risk and judgments. Additional influences are the quality of the information used, the assumptions and exclusions made, any limitations of the techniques and how they are executed."[631]

Although these influencing factors cannot be avoided, they should be acknowledged and documented as a part of the risk assessment. The EWG is not aware of any research pertaining to the impact of human factors on the evaluation of nonconformities in DNA analysis. This issue is not unique to the field of DNA analysis; therefore, it may be of value to all fields to study the variability in determining the level of risk in different scenarios.

When implementing a corrective action, FSSPs should consider what methods they are using to address the causes of the nonconformity. Is the method adding more checks? Does it require additional training? Is the action likely to correct the problem or simply introduce more opportunities for nonconformities? The addition of tasks or checks that simply remind analysts to avoid nonconformity in the future or alter the sequence of steps within a process may not be sufficient to prevent error (see ***Sec. 8.6.1*: *Checklists***). Furthermore, additional training, testing, or monitoring may create a resource burden, prompting analysts to be overly conservative during their interpretation or reporting of results and fearful of making future errors.

There is also the possibility of overcorrecting or undercorrecting an issue. A corrective action may remedy the initial nonconformity but result in an increased risk of a new nonconformity occurring. For example, a corrective action may result in the implementation of a new checklist, but if an analyst does not use the checklist or uses it incorrectly, a new nonconformity may occur. In contrast, the proposed solution may not prevent the nonconformity from recurring. Recognizing these factors and monitoring the outcome of a corrective action are critical to ensure an FSSP is handling nonconformities properly.

For a risk-based approach to nonconformities to be effective, those individuals evaluating nonconformities and the analysts who are interacting with the quality system should understand the process. This includes an understanding of the FSSP's risk criteria, the process of root cause

[631] International Organization for Standardization (ISO). *Risk Management Guidelines, ISO/IEC 31000:2018*. 2018. https://www.iso.org/standard/65694.html.

analysis, and the creation and implementation of corrective actions. Therefore, FSSPs should provide training opportunities for all individuals involved.

Recommendation 8.7: To improve consistency and reduce the potential for subjective or biased assessments, forensic science service providers should use a risk-based approach with documented guidance in the investigation and resolution of nonconformities. At minimum, a matrix or defined categories should be used to assess the risk of the nonconformity occurring or recurring and its impact on casework.

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Appendix 8.1: Standards and Guidance Documents Addressing Validity and Reliability

Multiple standards and guidance documents currently address the validity and reliability of analysis methods and validation:

- *ISO/IEC 17025: General requirements for the competence of testing and calibration laboratories (2017)*[632]
- *National Association of Testing Authorities (NATA): Validation and verification of quantitative and qualitative test methods (2018)*[633]
- *FBI: Quality Assurance Standards for Forensic DNA Testing Laboratories (2020)*[634]
- *ANSI/ASB Standard 020: Standards for Validation Studies of DNA Mixtures, and Development and Verification of a Laboratory's Mixture Interpretation Protocol, 1st Edition (2018)*[635]
- *ANSI/ASB Standard 040: Standard for Forensic DNA Interpretation and Comparison Protocols, 1st Edition (2019)*[636]
- *ENFSI: Recommended Minimum Criteria for the Validation of Various Aspects of the DNA Profiling Process, 1st Edition (2010)*[637]
- *ENFSI: Guidelines for the Single Laboratory Validation of Instrumental and Human Based Methods in Forensic Science (2014)*[638]
- *SWGDAM Validation Guidelines for Forensic DNA Analysis Methods*[639]
- *SWGDAM Guidelines for the Validation of Probabilistic Genotyping Systems*[640]

[632] International Organization for Standardization (ISO). *General Requirements for the Competence of Testing and Calibration Laboratories, ISO/IEC 17025:2017*. 2017. https://www.iso.org/standard/66912.html.

[633] National Association of Testing Authorities. *Guidelines for the Validation and Verification of Quantitative and Qualitative Test Methods. Technical Note 17*. 2012. https://www.demarcheiso17025.com/document/Guidelines%20for%20the%20validation%20and%20verification%20of%20quantitative%20and%20qualitative%20test%20methods.pdf.

[634] Federal Bureau of Investigation (FBI). *Quality Assurance Standards for Forensic DNA Testing Laboratories*. 2020. https://le.fbi.gov/file-repository/forensic-qas-070120.pdf/view.

[635] American National Standards Institute/Academy Standards Board. *ANSI/ASB Standard 020: Standard for Validation Studies of DNA Mixtures, and Development and Verification of a Laboratory's Mixture Interpretation Protocol*. 2018. https://www.aafs.org/sites/default/files/media/documents/020_Std_e1.pdf.

[636] American National Standards Institute/Academy Standards Board. *ANSI/ASB Standard 040: Standard for Forensic DNA Interpretation and Comparison Protocols*. 2019. https://www.aafs.org/sites/default/files/media/documents/Std_040_e1.pdf.

[637] European Network of Forensic Science Institutes (ENFSI). *Recommended Minimum Criteria for the Validation of Various Aspects of the DNA Profiling Process*. 2010. https://enfsi.eu/wp-content/uploads/2016/09/minimum_validation_guidelines_in_dna_profiling_-_v2010_0.pdf.

[638] European Network of Forensic Science Institutes (ENFSI). *Guidelines for the Single Laboratory Validation of Instrumental and Human Based Methods in Forensic Science, Version 2.0*. 2014. https://enfsi.eu/wp-content/uploads/2017/06/Guidelines-for-the-single-laboratory-Validation-of-Instrumental-and-Human-Based-Methods-in-Forensic-Sciene_2014-version-2.0.pdf.

[639] Scientific Working Group on DNA Analysis Methods (SWGDAM). *Validation Guidelines for DNA Analysis Methods*. 2016. https://www.swgdam.org/_files/ugd/4344b0_813b241e8944497e99b9c45b163b76bd.pdf.

[640] Scientific Working Group on DNA Analysis Methods (SWGDAM). *SWGDAM Guidelines for the Validation of Probabilistic Genotyping Systems*. 2015. https://www.swgdam.org/_files/ugd/4344b0_22776006b67c4a32a5ffc04fe3b56515.pdf.

9. Education, Training, and Professional Credentialing

9.1 Introduction and Scope

Forensic DNA analysis is a rapidly evolving field. As such, education (both foundational and continuing) and training have fundamental roles in supporting forensic science service providers (FSSPs) in their mission to provide high-quality, scientifically robust, and relevant results and opinions to the legal system. Despite the importance of education and training, there is a limited coordination of efforts among the forensic DNA community to provide standardized resources for these critical aspects. As such, FSSPs often develop and implement their own internal training programs and competency assessments.

Beyond initial training resources, access to continuing education resources may not be equal between FSSPs. Moreover, there is no universal requirement for professional credentialing (e.g., certification, licensure). As a result of the lack of community coordination and robust universal standards, the education, training, and professional credentialing requirements for DNA analysts vary depending not only on the jurisdiction and type of FSSP but also on the resources individual FSSPs are able to apply to these areas.

This chapter describes the current state of education, training, and professional credentialing opportunities in the forensic DNA community within the United States. The Expert Working Group (EWG) identifies gaps in the current state of these opportunities and offers an avenue for how to improve these by way of a proposed National Forensic DNA Training Consortium (NFDTC).

9.2 Formal Education Requirements

The DNA analyst's work requires a substantive level of expertise grounded in formal education on fundamental aspects of biology, chemistry, mathematics, probabilities, and statistics. The analyst must integrate and synthesize biological, physicochemical, probabilistic, and statistical concepts for effective, unambiguous, and accurate communications of the results obtained from the scientific procedures they perform. As technology becomes more sensitive and allows for more data generation, the skills needed to interpret and assess complex or ambiguous DNA profiles and subsequently communicate their significance and limitations to end-users and factfinders increase significantly. The following sections describe the current educational requirements for FSSP personnel.

9.2.1 Minimum Education Requirements

Most FSSPs that perform DNA analysis are accredited to the International Standard for Testing and Calibration Laboratories, known as International Organization for Standardization (ISO)/International Electrotechnical Commission (IEC) 17025 (see ***Sec. 8.2.3*: *Standards***). This

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standard requires laboratories to "document the competence requirements for each function influencing the results of laboratory activities, including requirements for education, qualification, training, technical knowledge, skills and experience."[641]

Those FSSPs accredited by the ANSI National Accreditation Board (ANAB) must comply with ANAB AR 3125, which specifies educational requirements for personnel based on the country in which they operate.[642] In the United States, "personnel who authorize results or express opinions and/or interpretations" in the biology discipline must possess "a baccalaureate or an advanced degree in a chemical, physical, or biological science or forensic science." Furthermore, the Federal Bureau of Investigations' Quality Assurance Standards (FBI QAS) delineates education requirements for Technical Leaders (TLs), casework Combined DNA Index System (CODIS) administrators, analysts, and technical reviewers.[643]

The FBI QAS also requires core subject area coursework requirements for these groups (with additional advanced degree specifications for TLs) in biochemistry, genetics, molecular biology, and statistics or population genetics.[644] In theory, by obtaining these minimum degree and curriculum requirements, FSSP personnel should be introduced to the following core knowledge, skills, and abilities (KSAs):

- Comprehension of general scientific and technical literature
- Ability to express scientific knowledge and methodology in written and oral forms
- Critical thinking
- Ability to comprehend, communicate, and assign probability and statistical values

With the introduction of complex statistical models used for DNA interpretation, coursework in probability and statistics is paramount for reporting analysts and technical reviewers. The FBI QAS added the minimum requirement for a course in statistics or population genetics for personnel hired, appointed, or promoted after July 1, 2020; however, personnel hired prior to this date may have completed either coursework *or* training as it pertains to statistics or population genetics.[645]

Although the FBI QAS education requirements provide a foundation for basic DNA casework, additional training is necessary to supplement this knowledge and ensure the analyst can

[641] International Organization for Standardization (ISO). *General Requirements for the Competence of Testing and Calibration Laboratories, ISO/IEC 17025:2017*. 2017. https://www.iso.org/standard/66912.html. *See* 6.2.2.

[642] ANSI National Accreditation Board (ANAB). *AR 3125: Accreditation Requirements for Forensic Testing and Calibration (2023)*. 2023. https://anab.qualtraxcloud.com/ShowDocument.aspx?ID=12371.

[643] Federal Bureau of Investigation (FBI). *Quality Assurance Standards for Forensic DNA Testing Laboratories*. 2020. https://le.fbi.gov/file-repository/forensic-qas-070120.pdf/view. *See* 5.

[644] Ibid. *See* 5.2.1, 5.3.1, 5.4.1, 5.5.

[645] Ibid. *See* 5.

understand the necessary scientific concepts as they relate to casework applications. Furthermore, certain aspects of complex DNA interpretation merit advanced education and training in the form of post-graduate coursework in DNA-specific interpretation concepts, such as how to address challenging samples or make suitability (for interpretation) decisions.

Analysts may benefit from additional education in population genetics and statistics as applied to forensic DNA analysis. Regardless of an analyst's education and coursework, training should be sufficient to ensure the KSAs required of the analyst are achieved prior to their authorization to perform casework analyses.

The FBI QAS does not have minimal education requirements for technicians or FSSP support personnel. Instead, these positions would defer to any minimum requirements the FSSP establishes as required by ISO/IEC 17025 and should be reflective of the tasks performed by these individuals. The impact of the work completed by FSSP support personnel within the system should be understood by the FSSP and the individuals performing the work, and training should be adequate to ensure that sufficient KSAs pertaining to the work they will perform are achieved (see **Sec. *11.6*: *Segmentation of Tasks***). This training is particularly important as every step in the DNA analysis process—from screening evidence for biological material to interpretation, reporting, and testimony—has an important and potentially outcome-determinative role in the process. Although the degree and coursework requirements described in this section can be satisfied by passing grades, as with all minimum requirements, FSSPs may choose to enact more rigorous requirements.

9.2.2 Undergraduate and Graduate Programs

In 2004, the National Institute of Justice (NIJ) published a report entitled *Education and Training in Forensic Sciences: A Guide for Forensic Science Laboratories, Educational Institutions, and Students*.[646] It contains recommendations for national standards in forensic science education and training. Based on these recommendations, the American Academy of Forensic Science (AAFS) established an accreditation program for collegiate forensic science programs known as the Forensic Science Education Programs Accreditation Commission (FEPAC).[647] The goal of FEPAC is to promote academic quality in forensic undergraduate- and graduate-level degree programs through accreditation.[648] However, a degree in forensic science (FEPAC-accredited or otherwise) should not be the sole route to employment at an FSSP. For example, graduates with

[646] National Institute of Justice (NIJ). *Education and Training in Forensic Science: A Guide for Forensic Science Laboratories, Educational Institutions, and Students*. 2004. https://www.ojp.gov/pdffiles1/nij/203099.pdf.

[647] American Academy of Forensic Sciences. Forensic Science Education Programs Accreditation Commission. Accessed March 23, 2024. https://www.aafs.org/FEPAC.

[648] Ibid.

non–forensic science degrees in biology or chemistry may have an excellent grounding in a fundamental science education that can be supplemented with forensic-specific training.

In order to gain FEPAC accreditation, a degree program must meet requirements to promote students' well-rounded exposure to core forensic science topics in undergraduate-level curriculum including "courtroom testimony, introduction to law, quality assurance, ethics, professional practice, and evidence identification, collection, processing."[649] The graduate-level curriculum expands on these topics and requires the following be part of the curriculum: "crime scene investigation, physical evidence concepts, law/science interface, ethics and professional responsibilities, quality assurance, analytical chemistry and instrumental methods of analysis, drug chemistry/toxicology, microscopy and materials analysis, forensic biology, and pattern evidence." [650] The FEPAC curriculum offers no specific guidance on core human factors considerations, and there is no explicit requirement to educate students on the topics of confirmation bias or contextual effects on perception and cognition, even though the importance of these considerations is widely acknowledged.

Aspiring DNA analysts in a FEPAC-accredited undergraduate program should follow the curricula requirements within the Criminalistic, Biology, or Chemistry concentrations as these tracks specify minimum semester hours of biology, physics, chemistry, mathematics, and forensic science courses. These FEPAC concentrations provide requirements for natural science coursework that align with the FBI QAS that other concentrations (e.g., Digital and Crime Scene) do not. FEPAC set forth these curriculum requirements to ensure that the student, at a minimum, develops an understanding of the areas essential to forensic science, acquires skills and experience in applying forensic science–based concepts to problem-solving, is oriented to professional values and ethics, and demonstrates gained knowledge through a formal capstone experience.[651]

Though these requirements do expose the student to basic forensic DNA processes and concepts, the current requirements afford substantive flexibility in designing university-based curriculum. The current nature of forensic DNA analysis, which is heavily rooted in physicochemical, statistical, probabilistic, and information technology, necessitates a reevaluation of current FEPAC requirements in favor of additional technical education that includes forensic statistics and probability, genetic theory and traditional molecular biology, data science, and general mathematics.

[649] Ibid.

[650] Ibid.

[651] Ibid.

This educational paradigm shift should focus on meeting the demands, needs, and fundamental background requirements of the modern DNA analyst to ensure they acquire an expert understanding of the processes and concepts that they interface with in their daily tasks. A more advanced and rigorous forensic biology curriculum should assist the student in developing a foundational understanding of the scientific and cognitive underpinnings of forensic DNA analysis and interpretation to better prepare them for DNA casework.

9.2.3 Portability of Qualifications – Education and Experience

The FBI QAS requires that "each analyst, technical reviewer, casework CODIS administrator, and technical leader shall have his/her education, experience, and training qualifications evaluated and approved during two successive, separate external audits."[652] As a result, a new analyst as well as an analyst who relocates to another FSSP within the United States must have their education and experience reviewed and approved by the FSSP's TL in addition to two external audit teams. If the requisite courses have titles that do not match the subjects listed in the FBI QAS (e.g., biochemistry, genetics), these groups will have to examine "pertinent materials such as a syllabus, letter from the instructor, or other document that supports the course content."[653] Repeating this approval process is inefficient.

The evaluation of education, and specifically coursework, is prone to variation in determining if a course meets the FBI QAS requirements. Many FSSPs perform a strict transcript review for specific course titles during the hiring process, while others rely on their human resources departments to screen applicant transcripts. Such screening can eliminate talented candidates who do not have certain course titles on their college transcripts. If the review during the hiring process is not rigid, a TL could subsequently determine that a closely titled course does not comply with the FBI QAS.

A new employee who cannot secure proper documentation of the integral content of the course would have to complete additional and potentially redundant coursework before being authorized to perform casework. Even worse, an audit team could flag coursework accepted at the point of hire and by a TL as insufficient. Since the review of transcripts by an audit team may occur up to four years after an analyst is qualified to perform casework (e.g., two external audits each occurring two years after the analyst is qualified), the FSSP would have to engage with the FBI's National DNA Index System (NDIS) Custodian to determine whether work completed by that analyst is acceptable.

[652] Federal Bureau of Investigation (FBI). *Quality Assurance Standards for Forensic DNA Testing Laboratories*. 2020. https://le.fbi.gov/file-repository/forensic-qas-070120.pdf/view. Section 15.2.1: Audits.

[653] Ibid. Section 5.2.1.3: Personnel.

Ideally, an applicant would know if their education satisfied the FBI QAS before applying for an analyst position. The Scientific Working Group on DNA Analysis Methods (SWGDAM) engaged with AAFS and FEPAC in 2022 to ensure that student members and FEPAC-accredited programs were aware of the FBI QAS educational requirements.[654] A centralized system for early evaluation of candidate transcripts would solve these problems—if licensing and certifying bodies as well as the FBI would accept its determinations. This could also reduce the burden on the FSSP's TL and FBI QAS audit teams to independently perform these reviews and the risk associated with disagreement by any of these reviewers. Even without a unified and simplified evaluation process, FEPAC-accredited programs should ensure the curricula for tracks used by aspiring analysts contain courses with contents and titles that match the requirements of the FBI QAS.

9.3 Training

Once employed by an FSSP, an analyst must undergo an FSSP-sponsored in-house training program with practical, written, or oral competency testing prior to being authorized to perform independent casework. The discussion of personnel training in this section refers to the initial training period at an FSSP to achieve this authorization. Competency testing is used to demonstrate that the analyst has acquired the KSAs needed to successfully perform the techniques learned and achieve a result that is acceptable as specified by the FSSP (see ***Sec. 8.9: Provision of Practice and Feedback Opportunities for Expertise Development***).[655]

DNA cases can vary in complexity and as such may require differing levels of expertise for wet laboratory work, interpretation of results, and technical or administrative review. Depending on how an FSSP structures the functions of their personnel, individual training needs may vary. For example, analysts or technicians involved in sample processing, but not in the interpretation of DNA profiles, may require less, or at least different, training than analysts who work across both areas.

Regardless of the type of personnel being trained, an FSSP is a series of interconnected parts, and decisions made at the various steps in the analytical and interpretive process can significantly impact final outcomes. Therefore, all personnel should be trained to understand the systems, decision points, quality processes, and outcomes that their work can impact (see ***Sec. 11.6: Segmentation of Tasks***). By employing a systems approach to training, all personnel should be

[654] American Academy of Forensic Sciences. SWGDAM Notice on QAS Educational Requirements. Accessed March 23, 2024. https://www.aafs.org/article/swgdam-notice-qas-educational-requirements?utm_source=swgdam-notice&utm_medium=email&utm_campaign=dec-9-newsletter.

[655] National Commission on Forensic Science. *Views of the Commission: Proficiency Testing in Forensic Science*. 2016. https://www.justice.gov/ncfs/page/file/839691/dl.

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able to predict the effect a certain treatment will have on final outcomes (see ***Sec. 3.3.5: Understanding Upstream and Downstream Effects***).

9.3.1 Governance and Standards for Training

FSSPs in the United States that participate in NDIS or receive federal grant funding are required to be accredited to and follow the FBI QAS, which contains requirements for training analysts and other FSSP personnel. These requirements, however, provide minimal guidance on the content and structure of a successful training program.

ISO/IEC 17025 requires that FSSPs "document the competence requirement for each function … including requirements for education, qualification, training, technical knowledge, skills and experience."[656] It adds that FSSPs shall "ensure that the personnel have the competence to perform laboratory activities for which they are responsible," and that records for competency, training, authorization, and monitoring of competence need to be maintained.[657]

ANAB's AR 3125[658] expands slightly on ISO/IEC 17025 by including specific areas in which analysts should be trained, including KSAs needed to perform work, general knowledge of forensic science and application of ethical practices, criminal and civil law, and testimony. AR 3125 also requires practical examination(s) that cover the range of anticipated tasks.

The FBI QAS adds requirements for forensic DNA analysis and grants the TL authority over the training program.[659] Overall, the FBI QAS requires that analysts be trained to the extent of their job duties, the training be documented, and competency tests be given prior to casework authorization. The FBI QAS also mentions training for reinterpretation of legacy data (i.e., data generated by a technology, platform, or kit that the FSSP no longer uses for DNA interpretation); training for technical reviewers, technicians, and FSSP support personnel; and retraining;[660] however, as with most standards, the specifics for what content to include and how to accomplish the requirements are left to the FSSP to develop.

There are also several standards for training on the Organization of Scientific Area Committees for Forensic Science (OSAC) Registry[661] such as the interdisciplinary ASTM E2917-19a *Standard Practice for Forensic Science Practitioner Training, Continuing Education, and Professional*

[656] International Organization for Standardization (ISO). *General Requirements for the Competence of Testing and Calibration Laboratories, ISO/IEC 17025:2017*. 2017. https://www.iso.org/standard/66912.html. Process Requirements – 7.8.1.1.

[657] Ibid. Process Requirements – 7.8.1.1.

[658] ANSI National Accreditation Board (ANAB). *AR 3125: Accreditation Requirements for Forensic Testing and Calibration (2023)*. 2023. https://anab.qualtraxcloud.com/ShowDocument.aspx?ID=12371. *See* 6.2.2.2.

[659] Federal Bureau of Investigation (FBI). *Quality Assurance Standards for Forensic DNA Testing Laboratories*. 2020. https://le.fbi.gov/file-repository/forensic-qas-070120.pdf/view. Section 6 - Training.

[660] Ibid. Section 6 – Training.

[661] Organization of Scientific Area Committees (OSAC). OSAC Registry. Accessed March 27, 2024. https://www.nist.gov/organization-scientific-area-committees-forensic-science/osac-registry.

Development Programs,[662] the ANSI/American Standards Board (ASB) Standard 022 *Standard for Forensic DNA Analysis Training Programs,*[663] and the more methodology-specific standards (e.g., ANSI/ASB Standard 116 *Standard for Training in Forensic DNA Quantification Methods*).[664] These standards describe more specific topics that an FSSP should incorporate into their in-house training program and provide direction pertaining to when information should be delivered via lectures or practical exercises and what competency testing should entail; however, standards on the OSAC Registry are optional for most FSSPs (see ***Sec. 8.2.3*: *Standards***).

Other optional guidance for training programs comes from the *SWGDAM Training Guidelines*.[665] The current version of the SWGDAM Training Guidelines, released in 2020, contains tasks, reading assignments, and suggested assessments to aid FSSPs in developing their in-house training program. Guidance is also available in the European Network of Forensic Science Institutes (*ENFSI) Guideline for the Training of Staff in Forensic DNA Laboratories*.[666] As with the OSAC Registry standards, there is no requirement that FSSPs follow these guidelines.

To have greater value and consistency between FSSPs, the EWG emphasizes the importance for training standards and guidance documents to be specific and precise. For example, having more specific guidance in the FBI QAS as to what the KSAs should include will help the FSSPs train more effectively. The KSAs for DNA interpretation could specify that the analyst should be trained to determine DNA profile suitability, estimate the number of contributors (NOC) in a sample, deconvolute a DNA mixture profile, and compare crime scene DNA profiles to known profiles. Several standards for training in DNA methods are on the OSAC Registry and incorporate more specific knowledge-based and practical training topics, which is a step towards improvement.[667] FSSPs should implement the OSAC Registry and ANSI/ASB training standards as well as use the ENFSI and SWGDAM training guidelines when developing or improving their in-house training programs.

[662] ASTM International. *ASTM E2917-19a: Standard Practice for Forensic Science Practitioner Training, Continuing Education, and Professional Development Programs*. 2022. https://www.astm.org/e2917-19a.html.

[663] American National Standards Institute/Academy Standards Board. *ANSI/ASB Standard 022: Standard for Forensic DNA Analysis Training Programs*. 2019. https://www.aafs.org/sites/default/files/media/documents/022_Std_e1.pdf.

[664] Organization of Scientific Area Committees (OSAC). OSAC Registry. Accessed March 27, 2024. https://www.nist.gov/organization-scientific-area-committees-forensic-science/osac-registry.

[665] Scientific Working Group on DNA Analysis Methods (SWGDAM). *SWGDAM Training Guidelines*. 2020. https://www.swgdam.org/_files/ugd/4344b0_5e228328339443bfb197942f2d99f579.pdf.

[666] European Network of Forensic Science Institutes (ENFSI). *Guideline for the Training of Staff in Forensic DNA-Laboratories*. 2022. https://enfsi.eu/wp-content/uploads/2022/03/Guideline-for-the-Training-of-DNA-Staff.pdf.

[667] Organization of Scientific Area Committees (OSAC). OSAC Registry. Accessed March 27, 2024. https://www.nist.gov/organization-scientific-area-committees-forensic-science/osac-registry.

9.3.2 In-House Training Programs

The goal of an in-house training program is to prepare FSSP personnel to perform their assigned tasks accurately, reliably, independently, and efficiently. Currently, FSSPs determine how they will meet the requirements of the FBI QAS, the standards they have implemented from standards developing organizations (SDOs), or in guidance documents from groups such as SWGDAM or ENFSI. As a result, training programs, competency requirements, and technical knowledge vary widely among FSSPs.

External evaluation (e.g., external audits, external assessments) to existing standards and recommendations seems to rely on the presence of certain features (e.g., orientations, reading assignments, documented completion assessments) in a training program to determine if the FSSP has met the standards, if the training is adequate, and if analysts completing the program will be prepared to perform independent casework once the training program is complete. Therefore, it is currently not difficult for FSSPs to demonstrate that they are complying with standards to maintain accreditation. To address the lack of guidance regarding DNA-relevant, foundational training content, several organizations have published recommended literature lists (see **Callout Box 9.1**).

In-house training programs should be regularly evaluated by both the FSSPs themselves and during accreditation to ensure that training program quality measures and requirements are applied. FSSPs could evaluate the efficacy of in-house training programs based on trainee performance on written/oral competency tests, through the results of performance monitoring (e.g., proficiency testing) after completion of the training program, and through trainee feedback.

The training program needs to be tailored to the needs of not only the FSSP but also the trainees and trainers. Some trainees may need more attention in certain areas, and the training programs should be able to adjust to those needs to ensure the analyst is equipped to perform independent casework upon completion of the training program. Although a "good" training program is not defined in existing standards, an effective training program should be one that ultimately prepares the analyst for the rigors of casework, including foundational knowledge of the different methodologies and technical knowledge of each technique used by the FSSP, and prepares the analyst to provide effective testimony.

Callout Box 9.1: Non-Exhaustive List of Resources for Locating Recommended Literature on Forensic DNA Analysis Topics

SWGDAM Training Guidelines:[668] This document lists publications and online resources for trainers and trainees. The literature covers a breadth of DNA topics including autosomal short tandem repeats (STRs), mixture interpretation, mitochondrial DNA (mtDNA), and other informative DNA markers. SWGDAM acknowledged that this list was not all-encompassing and recommended that FSSPs tailor the resources to fit their specific needs.

Informative Literature for Forensic Biology and DNA:[669] This draft document extends the 2020 SWGDAM Training Guidelines and is a comprehensive bibliography of textbooks, reviews, and research studies on forensic DNA topics. It was prepared by the Biology Scientific Area Committee of OSAC.

MVPs of Forensic DNA: Examining the Most Valuable Publications in the Field:[670] This resource builds on the two documents listed above. It contains nearly 500 references across 25 aspects of forensic DNA topics.

Research Forensic Library:[671] A curated collection of publicly accessible materials relating to many forensic science disciplines. This online library is hosted by Florida International University and partially funded through a cooperative agreement with the NIJ.

9.3.3 Training Content Gaps

In addition to the lack of specificity of training content regarding foundational KSAs, there are several areas related to human factors where DNA analysts would benefit from additional training. As discussed in ***Sec. 3.3.3*: Cognitive and Contextual Bias and Impacts on Decision Points in DNA Analysis**, cognitive bias may have detrimental effects on DNA interpretation. To reduce the effects of cognitive bias on DNA interpretation, DNA analysts should be trained on topics such as the impact of various human factors and approaches to mitigate them (e.g., the need to assess the quality and suitability of DNA profiles prior to DNA comparisons to minimize confirmation bias). To equip FSSPs with training materials that cover these topics, SDOs should develop training standards discussing human factors content as it relates to DNA interpretation.

It Is impossible to overstate the challenges analysts face during testimony. Understanding an analyst's role as an expert witness and being able to explain complex scientific concepts correctly requires training, preparation, practice, assessment, and feedback. In addition, most new analysts have very little exposure to the procedures and proceedings within a courtroom. Increasing familiarity with court rules and procedures during a trial (e.g., swearing in under oath,

[668] Scientific Working Group on DNA Analysis Methods (SWGDAM). *SWGDAM Training Guidelines*. 2020. https://www.swgdam.org/_files/ugd/4344b0_5e228328339443bfb197942f2d99f579.pdf.

[669] Organization of Scientific Area Committees (OSAC). *Informative Literature for Forensic Biology and DNA*. 2020. https://www.nist.gov/system/files/documents/2021/03/26/Informative%20Literature%20for%20Forensic%20Biology%20and%20DNA%20-10-26-20.pdf.

[670] Butler JM, Cotton RW, Prinz M, Word C. MVPs of Forensic DNA: Examining the Most Valuable Publications in the Field. 2021 AAFS Virtual Meeting, Virtual American Academy of Forensic Sciences, 2021. https://strbase.nist.gov/NIST_Resources/Presentations/2021/AAFS2021-W19-Handouts.pdf

[671] Florida International University. Research Forensic Library. Accessed March 27, 2024. https://forensiclibrary.org/.

voir dire, direct and cross-examination, objections) will help the analyst focus on presenting their findings in a clear and concise manner without distraction from these events.

The FBI QAS requires in-house training programs to "include an assessment of oral communication skills and/or a mock court exercise."[672] ANSI/ASB Standard 022 *Standard for Forensic DNA Analysis Training Programs*[673] and the corresponding methodology-specific training standards[674] describe training content in more detail and what KSAs may be assessed during a mock trial. However, being proficient in testimony extends beyond solely possessing expertise in the foundational scientific content. There needs to be more robust training on the intricacies of providing testimony (see **Chapter *6*: *Pre-Trial Preparation and Testimony***).

Moreover, there are no requirements or best practice guidance for oral communication skills during mock trial assessments. To improve the efficacy of mock trial exercises, SDOs should delineate the minimum KSAs that should be assessed, a standard set of foundational questions to be used during the exercise, guidance on the appropriateness of determining when and how criminal justice partners should be involved, and minimum passing criteria. In the meantime, to address these shortcomings, FSSPs should explicitly address these gaps in their training manuals or standards.

Beyond testimony training, the EWG has identified additional training content gaps that span beyond those individuals who will be tasked with testifying on DNA results. These gaps relate to quality personnel, TLs, and analysts:

- Senior analysts and individuals responsible for QA/QC should have training in effective root-cause analysis procedures, risk assessment for nonconforming work especially if retroactive case review is warranted, and legal disclosure obligations. Individuals involved in validations should also have training on ethical sample collection (see ***Sec. 8.3.3*: *Peer Review of Internal Studies***).
- For TLs, advanced-level training in complex mixture interpretation, how to properly review validations, leadership concepts, professional responsibility, conflict resolution, root-cause analysis, legal disclosure obligations, and general human factors in decision-making should be among additional required training content (see ***Sec. 10.3.1.3*: *FSSP Management and Leadership***).
- For new analysts, specialized training in proper evidence handling and evidence integrity, the principles of interpretation, reporting and testimony of case results,

[672] Federal Bureau of Investigation (FBI). *Quality Assurance Standards for Forensic DNA Testing Laboratories*. 2020. https://le.fbi.gov/file-repository/forensic-qas-070120.pdf/view. Section 6 - Training.

[673] American National Standards Institute/Academy Standards Board. *ANSI/ASB Standard 022: Standard for Forensic DNA Analysis Training Programs*. 2019. https://www.aafs.org/sites/default/files/media/documents/022_Std_e1.pdf.

[674] American Academy of Forensic Sciences Standards Board. *ANSI/ASB Standard 115: Standard for Training in Forensic Short Tandem Repeat Typing Methods Using Amplification, DNA Separation, and Allele Detection*. 2020. https://www.aafs.org/sites/default/files/media/documents/115_Std_e1.pdf.

human factors, and professional responsibility and legal disclosure obligations should be included in their training content. This specialized training could be covered, with practical assessments, through the development of the NFDTC (see ***Sec. 9.6.4: Curriculum and Providers***).

The training of quality personnel, TLs, and DNA analysts should not be limited to their individual duties. FSSP personnel should be encouraged, supported, and required to pursue continuing education (CE), which includes training on emerging trends, techniques, and technologies (see ***Sec. 9.5: Continuing Education***). Additionally, FSSP management should provide analysts with regular training exercises composed of sample types that are representative of samples encountered in casework (e.g., complex mixtures, samples that may be error-prone, or uninformative samples). The grading of training samples should come with instructive feedback on performance, enabling the analyst to learn from the process to improve upon their performance (see ***Sec. 8.9.1: Training Exercises to Maintain and Increase Expertise***).

Recommendation 9.1: In addition to technical competency, forensic science service providers should require DNA analysts and DNA Technical Leaders to demonstrate understanding of the following subject areas, as appropriate to their role:

- **Human factors in forensic DNA analysis and interpretation**
- **Root-cause analysis**
- **Professional responsibility under applicable Codes of Conduct**
- **Constitutional, statutory, and other disclosure obligations**
- **How to maintain independence and avoid errors during testimony**
- **How to communicate forensic statistical concepts and scientific limitations to factfinders**

9.3.4 Current Method to Test and Evaluate Trainees

Accreditation standards and the FBI QAS address overall FSSP and position-specific training and competency testing requirements. Specifically, Standard 6.1.3 of the FBI QAS requires assessment of "the technical skills and knowledge required to perform DNA analysis."[675] Despite this inclusion, there is no discussion on what KSAs should be included in the trainee's assessment or how the assessment should be conducted. This is comparable to the lack of guidance provided

[675] Federal Bureau of Investigation (FBI). *Quality Assurance Standards for Forensic DNA Testing Laboratories*. 2020. https://le.fbi.gov/file-repository/forensic-qas-070120.pdf/view. Standard 6.1.3.

for topics that should be embedded in internal training curriculum (see ***Sec. 9.3.1*: Governance and Standards for Training**).

Typically, a trainee's assessment is developed and conducted by an FSSP and can include written closed- or open-book examinations, oral examinations, interpretation exercises, or practical exercises. Standard 6.1.4 of the FBI QAS lists a requirement of an oral communication skills assessment or a mock trial component, but there is no standard set of oral questions or specific mock trial criteria.[676] Furthermore, Standard 6.3.1 indicates that "competency testing for a new analyst shall include a practical component and written and/or oral components."[677] As a result of these broad standards, FSSPs assess their own trainees. The implementation and rigor of these assessments may lead to a variation in analyst competency between FSSPs. An expectation of competency testing is that the analyst "has [achieved the] technical skills and met minimum standards of knowledge necessary to perform the forensic DNA analysis,"[678] and while not explicitly stated, is therefore able to get the correct answer when using approved and validated methods.

If an analyst who has previously conducted casework is later removed from a training program for unsuitability or incompetence, the FSSP should examine whether disclosure or corrective action vis-a-vis casework is required. The removal of an individual from a training program can be a complex matter involving the FSSP's human resources department and, potentially, legal departments. Nonetheless, the FSSP should have the ability to identify personnel that may not be suited for the tasks of an analyst and either reassign that individual to another position or provide them with alternate tasks for which they may be better suited.

9.3.5 Reducing Variability in Trainee Assessment

To mitigate the variation in FSSP-specific assessments, competency tests need to be standardized, both in content and in type of testing. The first step towards a more consistent system of competency testing will occur as individual FSSPs incorporate OSAC Registry and ANSI/ASB training standards and the *SWGDAM Training Guidelines* into their training programs. These standards and guidelines comment on types of assessment methods and guide FSSPs toward a more consistent baseline of the foundational KSAs needed by analysts.

With FSSPs developing their training programs around the same foundational training standards and guidelines, FSSPs should then be assessing their analysts on similar training content—at least

[676] Ibid.

[677] Ibid. Standard 6.3.1.

[678] Scientific Working Group on DNA Analysis Methods (SWGDAM). *The Guidance Document for the FBI Quality Assurance Standards for Forensic DNA Testing and DNA Databasing Laboratories*. 2020. https://www.swgdam.org/_files/ugd/4344b0_2bce9398b6a640fdb626063469939151.pdf.

from a foundational perspective. To the extent that SDOs incorporate more specificity to their training standards, and the more federal nonregulatory agencies, academic institutions, nonprofits, and other organizations that offer tools and resources for FSSP implementation, the more the criminal justice community will benefit from increased rates of implementation and standardization. The next step is to integrate the KSAs defined in these training standards and guidelines into standardized assessments. One method for providing a universal written assessment for the foundational knowledge required for DNA analysis is certification or a similar form of credentialing (see ***Sec. 9.4.1: Professional Certification***).

Beyond written and oral assessments, FSSPs often design and prepare their own sample sets for practical assessments or use proficiency test samples that may not test the breadth of sample complexity. As a result, the rigor of the practical assessments varies between FSSPs. A federal nonregulatory agency, academic institution, or nonprofit organization could provide practical standardized assessment samples to be used in conjunction with FSSP written and oral assessments. Not only would these sample sets provide standardization between FSSPs, but they would also relieve a burden on trainers to prepare their own in-house practical examinations (see ***Sec. 8.3.2: Validation and Requirements to Implement New Practices***).

9.3.6 Standards and Expectations for Trainers

In addition to variation between the content of FSSPs in-house training programs, the qualifications and quality of trainers may vary. For some FSSPs the trainer is the TL; for others, the trainer is a training coordinator (see ***Sec. 9.3.7: Training Coordinator***); while for some FSSPs, the trainer is a senior analyst who may also be juggling casework, court, and other responsibilities.

This variation in trainers stems from FSSPs having discretion in who they select to be the trainers for their in-house training program. The FBI QAS specifies the qualifications and education required for a TL, CODIS administrator, analyst, and technical reviewer but not for a trainer.[679] The individuals selected to serve as internal trainers should be competent in the techniques performed at the FSSP and should have gone through proper training to achieve competence before stepping into this role.

Being a competent casework analyst is one requirement for a trainer, but this alone does not always translate into being an *effective* trainer. Therefore, to better help the trainer prepare and teach analysts, the training standards prescribed by the FBI QAS and other SDOs should address the qualifications necessary to become a trainer and the additional training competency required

[679] Federal Bureau of Investigation (FBI). *Quality Assurance Standards for Forensic DNA Testing Laboratories*. 2020. https://le.fbi.gov/file-repository/forensic-qas-070120.pdf/view.

of these individuals. Training content may include pedagogical techniques, theories associated with learning skills, and communication effectiveness.

All training coordinators and trainers should have access to information relevant to training and teaching methodology. Trainers should be required to study this material and demonstrate their ability to employ these concepts prior to assuming their role as a trainer. Training efforts, support, and access to resources could be coordinated with universities, federal nonregulatory agencies, nonprofit organizations, or other organizations such as the Association of Forensic DNA Analysts and Administrators or the American Society of Crime Laboratory Directors (ASCLD).

9.3.7 Training Coordinator

Independent from the individuals who provide training, FSSPs should designate at least one individual to function as a *training coordinator*. A training coordinator is responsible for designing, implementing, and managing the training program for FSSP personnel. The coordination of training is often fulfilled by the TL, supervisor(s), or the analyst(s) responsible for training, but there is no requirement that a training coordinator be a technical subject matter expert. Designating a training coordinator may remove or alleviate some of the TL or analysts' administrative burden, allowing them to focus on providing technical training. FSSPs with more than one training coordinator should ensure these individuals are working together to maintain consistency across the FSSP's discipline sections.

One of the roles of the training coordinator is to ensure that all analysts, TLs, and other FSSP personnel receive the necessary training to perform their job duties effectively and efficiently, as well as meeting any accreditation or certification requirements. The training coordinator may also be responsible for creating and maintaining training records, assessing the effectiveness of the training program, and identifying areas for improvement. While a training coordinator with subject matter expertise may be responsible for developing and delivering training materials, including presentations, handouts, and assessments, a training coordinator that oversees training from a non-technical perspective should have awareness of different pedagogical methods to improve the understanding of adult learners. It is recognized that not all FSSPs have the demand for a full-time training coordinator even if this individual is responsible for multiple disciplines. Alternatively, FSSPs may benefit from a DNA discipline-specific training coordinator to focus on the development of training materials, mock samples, and challenging data specific to the needs of the FSSP.

The benefit of a designated training coordinator is that this individual has awareness of the training occurring across the FSSP's workforce or DNA section. A training coordinator should assume more of a supervisory or administrative role so that they can concentrate on overseeing the training program without the pressures of day-to-day casework. While it is encouraged that

This publication is available free of charge from: https://doi.org/10.6028/NIST.IR.8503

trainees get exposure to the approaches, skills, and experience of multiple trainers or mentors, the training coordinator can ensure that any identified gaps in learning are effectively addressed. Additionally, a centralized training coordinator can ensure all personnel are receiving the training necessary to maintain and advance their KSAs. The training coordinator may facilitate CE opportunities across the workforce, organize ongoing training exercises (see ***Sec. 8.9.1: Training Exercises to Maintain and Increase Expertise***), and ensure that the FSSP's training program stays current as new methods and technologies are introduced within the FSSP.

The training coordinator should ensure the FSSP's training program aligns with current accreditation standards as well as other relevant training standards and guidelines previously discussed in this chapter (see ***Sec. 9.3.1: Governance and Standards for Training***). Having a training coordinator assigned the task of reviewing and updating the training manuals, in coordination with the TL, to reflect current standards and best practices can increase the efficiency of these efforts as this individual increases their familiarity with the breadth of requirements. Upon establishment of the NFDTC (see ***Sec. 9.6: Recommendation for a National Forensic DNA Training Consortium***), the training coordinator could serve as the liaison between the NFDTC and the FSSP.

A designated training coordinator may not be feasible for all FSSPs. However, FSSP management should dedicate resources to have at least one individual whose responsibilities include:

- Identifying and guiding the FSSP towards effective evidence-based training methodologies and updating the in-house training program to reflect evidence-based best practices.
- Assessing the FSSP's in-house training program annually.
- Ensuring compliance with applicable standards on education and training.
- Coordinating with the TL to ensure that changes to the in-house training program are reviewed and approved as required by the FBI QAS.
- Coordinating with the NFDTC, once established (see ***Sec. 9.6: Recommendation for a National Forensic DNA Training Consortium***).

9.4 External Oversight: Certification and Licensure

External oversight provides a mechanism for demonstrating that analysts possess the foundational KSAs and keep abreast of emerging research, technology, and evolving science in their field. This oversight is performed by organizations external to the FSSP and currently includes professional certification and licensing. While certification is typically one way for demonstrated knowledge to be verified by a third party, licensure is a tool that allows the government, or other authority, to regulate a profession and ensure that practitioners meet

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certain standards of competence *and* ethical conduct. Licensure can grant legal authority or permission to practice a profession.

Many other professions, including teachers, physicians, cosmetologists, dentists, attorneys, social workers, real estate agents, and dietitians, require certification or licensing. Yet, despite forensic science having an impact on life and liberty, there is no such nationwide requirement for practitioners in this field. As of June 2022, "twenty-one states and Washington, D.C. currently have statutorily created or created by another means forensic science state commissions or oversight bodies,"[680] with varying levels of investigative and regulatory authority.

9.4.1 Professional Certification

Certification is a third-party evaluation through a written assessment that an individual has acquired specialized knowledge and technical comprehension needed in their profession.[681] Certification serves as a bridge between an analyst's education and training as it "involves objective review of academic degrees, minimum mandatory experience in the discipline, and successful completion of a written examination."[682]

Several national committees have stressed the importance of certification.[683] Reasons to support certification include establishing a minimum competency for forensic practitioners by testing knowledge-based technical acuity, requiring some type of CE or engagement in the specialty area(s) of certification, and establishing a code of ethics that forensic practitioners should agree and adhere to. Despite this, certification is currently optional for analysts in most FSSPs.

Melbourn et al.[684] conducted a survey of 73 forensic practitioners regarding opinions on certification. Generally, the respondents supported mandatory certification; however, when asked why a forensic science practitioner may not want to become certified, respondents reported several reasons. These included the costs of the certification/recertification process, the costs of training to maintain certification (if not covered by an employer), fear of failing the certification examination, and not seeing any benefit to being certified since it is not required for

[680] Ropero-Miller JD, Jones N. *Forensic Science State Commissions and Oversight Bodies—a 2022 Update*. Washington, DC. 2022. Forensic Technology Center of Excellence. doi: 10.4324/9780429326530. https://forensiccoe.org/private/6387e3c0cb5a7.

[681] National Commission on Forensic Science. *Views of the Commission: Certification of Forensic Science Practitioners*. 2016. https://www.justice.gov/ncfs/page/file/905897/dl.

[682] National Institute of Justice (NIJ). *Education and Training in Forensic Science: A Guide for Forensic Science Laboratories, Educational Institutions, and Students*. 2004. https://www.ojp.gov/pdffiles1/nij/203099.pdf.

[683] National Research Council, Committee on Identifying the Needs of the Forensic Science Community. *Strengthening Forensic Science in the United States: A Path Forward*. The National Academies Press: Washington, DC, 2009. doi:10.21428/cb6ab371.b2d683d2.

[684] Melbourn H, Smith G, McFarland J, Rogers M, Wieland K, DeWilde D, Lighthart S, Quinn M, Baxter A, Quarino L. Mandatory Certification of Forensic Science Practitioners in the United States: A Supportive Perspective. *Forensic Science International: Synergy*. 2019; 1:161-9. doi:10.1016/j.fsisyn.2019.08.001.

their position. These factors may explain why FSSPs have been slow to adopt and implement a certification requirement for analysts.

Historically speaking, certification options for analysts have been limited to the American Board of Criminalistics (ABC).[685] Early exams, offered since the 90s, not only focused on a specific forensic discipline under assessment but also required analysts to take the General Knowledge Examination, which covered a wide range of forensic science topics.[686] For DNA analysts, the specialty examination was the Molecular Biology Examination, and this certification covered forensic topics beyond forensic DNA analysis. This meant that an individual who may possess the desired KSAs for a DNA analyst was required to prepare beyond their specialty to obtain certification.

The ABC's Molecular Biology Examination was retired in July 2023. In its place are the new Forensic DNA and Biological Evidence Screening examinations.[687] In 2021, the ABC began accepting applications for both new examinations. With the removal of the general core knowledge questions, these new certification examinations are designed to focus solely on foundational knowledge needed for each specialty area. These examinations were held to higher standards in test development because of ABC's goal to obtain ISO/IEC 17024:2012 accreditation.[688] Compared to the Molecular Biology Examination, these examinations better address the specialty subject matter relevant to serology and DNA analysis and will provide a more comprehensive assessment.

A certification examination does assess knowledge-based technical comprehension, but it does not assess an individual's practical hands-on laboratory skills and abilities. Indeed, given the diversity of DNA methods used by FSSPs across the country and the requirements of ISO/IEC 17024 accreditation, the development of an accredited practical examination for certification would be extremely challenging to develop and maintain.

Certification helps with standardizing the foundational technical knowledge assessment for analysts; however, it is essential that certification does not give the individual, FSSP, customer, or factfinder a false sense of security regarding the KSAs of the certified individual or the accuracy and reliability of the results produced, as certification is only one component of a QA/QC program. Additionally, certification requires tremendous preparation, especially for experienced analysts

[685] American Board of Criminalistics. American Board of Criminalistics History. Accessed March 23, 2024. https://www.criminalistics.com/history.html.

[686] Ibid.

[687] American Board of Criminalistics. Forensic DNA Examination. Accessed March 23, 2024. https://www.criminalistics.com/forensic-dna.html.

[688] ANSI National Accreditation Board (ANAB). Personnel Certification under ISO/IEC 17024: American Board of Criminalistics, Inc. Accessed March 23, 2024. https://anabpd.ansi.org/Accreditation/credentialing/personnel-certification/AllDirectoryDetails?&prgID=201&OrgId=152501&statusID=4.

who may have had their initial education and training many years ago. Therefore, there needs to be a sufficient cost benefit for the effort from both the FSSP and the analyst.

9.4.2 Recertification

Certification promotes the importance of CE through its recertification structure (see ***Sec. 9.5: Continuing Education***). ABC-certified analysts are required to be recertified every five years, and this is accomplished by acquiring specialty points.[689] Analysts can obtain specialty points by attending national or regional conferences, attending workshops and trainings, performing internal technical audits, performing external assessments, publishing a technical paper within the certification discipline, and various other mechanisms including presenting technical trainings.[690]

A recertification point structure helps to ensure that analysts remain involved in the greater forensic DNA community and consistently seek opportunities for CE within their specialty area; however, it can be burdensome for FSSPs or analysts that are impacted by limited financial and personnel resources. Oftentimes, funds dedicated towards training are the first to be negatively impacted during budget cuts, forcing CE to fall to the analyst's own discretion and monetary capacity. Prioritizing CE as an essential function, FSSPs should incorporate certification renewal considerations into training budgets.

9.4.3 Professional Licensure

Texas is the only state in the United States that requires forensic analysts and technicians to be licensed. The Texas Association of Crime Laboratory Directors developed a licensure program (see ***Appendix 9.1***) in recognition of some of the limitations of certification and to provide a mechanism for removing an analyst's ability to practice in cases of misconduct, which is a common component of licensure in a wide range of professions. The aim of the program was not to replicate certification but rather to focus on the challenging issues facing all forensic analysts as part of the legal system.

The Texas Forensic Science Commission's (TFSC's) licensure program includes a Forensic Analyst General Examination. This examination explores topics related to the intersection between the FSSP and the criminal justice system. Unlike the ABC's certification program, the TFSC's Forensic

[689] American Board of Criminalistics. Certification. Accessed March 23, 2024. https://www.criminalistics.com/certification.html.

[690] American Board of Criminalistics. *Recertification Point Structure*. 2020. https://www.criminalistics.com/uploads/3/2/3/3/32334973/recertification_point_structure.pdf.

Analyst General Examination does not assess the knowledge-based technical aspects present in DNA analysis. Instead, this examination covers the following subject areas:[691]

1. Evidence Handling
2. Legal Disclosure Obligations under *Brady v. Maryland* and the Michael Morton Act
3. Basic Statistics for Forensic Application and Related Concepts
4. Expert Testimony
5. Professional Responsibility
6. Human Factors
7. Root-Cause Analysis

The TFSC's ability to discipline licensees is a tool to ensure individuals who violate core values held by the Texas forensic science community are not allowed to gain employment in other Texas-based FSSPs. The TFSC's website includes a profile for each licensed analyst, including their employing FSSP, and an indication of whether their license is in good standing.[692] This is like the websites found in other professions (e.g., State Bar Associations) in all 50 states. The importance of this tool cannot be overstated, given the critical nature of the work performed by FSSPs. Unfortunately, without other states adopting licensure programs, there is no reciprocal ability to obtain similar information about analysts in other states.

A nationwide license requirement modeled on the Texas approach would mean state legislative changes and investment of state resources to devote to a multidisciplinary development effort between many criminal justice partners, which may be challenging to implement in some states. However, external oversight and professional credentialing of FSSP personnel through a combination of certification and licensure provides a means to demonstrate foundational educational attainment and continued development, as well as a means of ensuring clearly stated expectations and a process for disciplinary action in the context of misconduct.

9.5 Continuing Education

CE is an important staple in many professions as the knowledge base of the professional should not stop expanding after training. CE is also a tool in promoting a learning organization (see ***Sec. 10.7: Learning Organization*** and ***Sec. 10.7.1: Individual, Team, and Organizational Learning***). The field of forensic DNA continues to advance both epistemologically and technologically and

[691] Texas Courts. *Texas Forensic Science Commission Analyst and Technician Licensing Examination Basic Information Regarding Examination Content, Scoring and Syllabus*. https://www.txcourts.gov/media/1442019/licensingexamsyllabus_071918.pdf.

[692] Texas Forensic Science Commission. Licensees. Accessed March 27, 2024. https://fsc.txcourts.gov/LicenseePublic.

as such, some techniques and procedures learned by analysts 10 years ago are now obsolete, making CE a necessity.

The FBI QAS provides a professional development framework for maintaining the TLs', CODIS administrators', analysts', and technical reviewers' technical qualifications via participation in activities that expand their knowledge and awareness of topics relevant to the field of DNA analysis. The standard mandates that a minimum of eight CE hours be obtained within each calendar year through attendance at "seminars, courses, professional meetings, or other documented lectures or classes in relevant subject areas," with online-based education formats necessitating approval by the FSSP's TL.[693] Irrespective of the number of CE hours required, if the CE materials are not providing relevant, useful information for the enhancement of discipline-specific knowledge, requiring and obtaining CE hours is done with no discernible purpose.

FSSP management should provide adequate support (e.g., time and funding) for FSSP personnel not only to meet the required CE hours set forth by the FBI QAS but also to ensure that the CE hours obtained are from relevant, high-quality sources. Additionally, depending on the job functions and requirements of the analyst, the EWG believes that eight hours of CE a year is not sufficient to keep up with advancing knowledge in DNA analysis. For comparison, in Switzerland, forensic geneticists are required to obtain 80 hours of CE per year.[694] A first step towards improving the current landscape of CE would be for analysts to meet the requirements of ASTM E2917-19a and obtain "an annual average of at least 16 hours [per year] of continuing education or professional development...over a three-year period."[695] The discussion in the following sections highlights the importance of CE through conference, seminar, and workshop attendance; external training options; and keeping up with current and emerging technologies.

9.5.1 Conference, Seminar, and Workshop Attendance

National and regional conferences are one of the customary means of distributing information to FSSPs and associated criminal justice partners regarding technological advances and current topics of discourse. However, despite these conferences being a main route of communication throughout the forensic community, their attendance can be limited by budgetary, casework load, and personnel constraints of the FSSP.

While conference attendance is oftentimes expensive and frequently requires out-of-town travel, the EWG believes it is worth the resource investment. By attending conferences of any scale, the

[693] Federal Bureau of Investigation (FBI). *Quality Assurance Standards for Forensic DNA Testing Laboratories*. 2020. https://le.fbi.gov/file-repository/forensic-qas-070120.pdf/view.

[694] Swiss Society of Legal Medicine. *Guidelines for Obtaining the Title "Forensic Geneticist SSLM"*. 2021. https://sgrm.ch/inhalte/Forensische-Genetik/Titelreglement_Forensische_Genetik_2021.pdf.

[695] ASTM International. *ASTM E2917-19a: Standard Practice for Forensic Science Practitioner Training, Continuing Education, and Professional Development Programs*. 2022. https://www.astm.org/e2917-19a.html.

analyst has an opportunity to see cutting-edge technology from vendors, interact with analysts from other FSSPs, learn about other FSSPs' approaches to casework, learn from presented case studies, and gain exposure to emerging research and take this information back to their FSSP for dissemination throughout the organization. Limiting this experience to a handful of analysts within a given year due to funding limitations or casework priorities means that in some FSSPs, it may take several years before an analyst is given the opportunity to attend another conference, during which time significant changes in the discipline may have occurred.

If analysts, TLs, and FSSP management are hindered in attending conferences, FSSPs may not be aware of current trends and may not be providing the appropriate services for their criminal justice partners. To address lack of resources to send analysts to annual conferences, many FSSPs have implemented a practice that requires analysts to disseminate conference-learned information (through a presentation or written report) to the rest of the FSSP personnel upon their return. Although helpful, this is not an acceptable substitute for the advantages of attending conferences and should not be considered CE for those who did not attend the conference.

As a result of the COVID-19 pandemic, the forensic science community has needed to acclimate learning through various virtual platforms. While online learning does not offer the same networking and in-person learning opportunities, the rise of virtual conferences and online training courses has made these offerings more accessible and diverse along with decreasing the cost and time constraints.[696] The use of virtual learning opportunities should continue to ensure more affordable and accessible CE and training opportunities for analysts. While in-person conference attendance remains vitally important for forensic community learning, engagement, and networking and should not be supplanted by virtual alternatives, to increase conference accessibility, larger conferences (e.g., AAFS, International Symposium on Human Identification, Bode Technology) should continue to provide virtual alternatives (e.g., specific hybrid/virtual streams) established during the COVID-19 pandemic.

9.5.2 External Training

External training courses provide another source of CE that often involves specialized training in instrumentation, software, or statistics. These courses are usually led by vendors who have sold, or intend to sell, their product to the FSSP. Thus, these offered trainings may have an embedded vendor-specific aspect, which can be beneficial depending on the analyst's or FSSP's needs. In instances where external training courses not specific to a product or vendor would better suit the analyst's or FSSP's needs, there may be greater benefit in attending online or in-person

[696] Sarabipour S. Research Culture: Virtual Conferences Raise Standards for Accessibility and Interactions. *Elife*. 2020; 9:e62668. doi:10.7554/eLife.62668.

vendor-neutral training courses led by universities such as the University of Lausanne,[697] learning institutions such as the Global Forensic and Justice Center at Florida International University,[698] or the Center for Statistics and Applications in Forensic Evidence (CSAFE).[699]

9.5.3 Keeping Up with Critical and Emerging Literature

The FBI QAS requires the TL to approve a program that structures the annual review of scientific literature to aid in the documentation of analysts' ongoing reading of scientific literature. Furthermore, the FBI QAS requires the FSSP to maintain or have access to a collection of "current books, reviewed journals, or other literature applicable to DNA analysis" for analysts to further their education and stay abreast of topics relevant to the field.[700]

The FBI QAS does not define a specific literature requirement (e.g., minimum reading requirement) or provide minimum requirements regarding the development of the program, nor does it require an assessment to be taken based on the reading. As such, developed literature monitoring programs are likely to have variation among FSSPs. To mitigate variation in access to literature, analysts should have equal access to a central repository of literature and content relevant to DNA analysis and developments in the field (e.g., those listed in **Callout Box 9.1**).

With the ongoing demands of backlogs, court, and casework requirements, FSSP management may give lower priority to continuing engagement with emerging literature than other responsibilities. FSSP management should provide analysts with adequate support such as access to relevant journals and dedicated working hours for staying current on publications and other resources. One example could be for FSSP management to allow analysts one day a month to cease casework activities so that they can focus on professional development. This could include time to read relevant literature, conduct journal clubs with their peers, watch webinars, or even observe testimony. In addition to being beneficial for analysts, having time set aside each month could help FSSP management show analysts that training in this area is a priority (see ***Sec. 10.7: Learning Organization).*** Moreover, it is valuable not only to have access to and read literature but also to also engage in discussion with peers concerning topics presented through the literature.

[697] Biedermann A, Hicks T, Voisard R, Taroni F, Champod C, Aitken C, Evett IW. E-Learning Initiatives in Forensic Interpretation: Report on Experiences from Current Projects and Outlook. *Forensic Science International*. 2013; 230(1-3):2-7. doi:10.1016/j.forsciint.2012.10.011.

[698] Florida International University. Science Serving Justice. Accessed March 27, 2024. https://gfjc.fiu.edu/.

[699] Center for Statistics and Applications in Forensic Science (CSAFE). Online Courses. Accessed January 15, 2024. https://learn.forensicstats.org/.

[700] Federal Bureau of Investigation (FBI). *Quality Assurance Standards for Forensic DNA Testing Laboratories*. 2020. https://le.fbi.gov/file-repository/forensic-qas-070120.pdf/view.

9.6 Recommendation for a National Forensic DNA Training Consortium

As discussed throughout this chapter, there are considerable gaps and variability in the current training, education, and professional credentialing opportunities offered to prepare, evaluate, and continue to educate analysts in the United States. FSSPs lack a centralized resource for educating and training analysts who emerge from undergraduate- or graduate-level degree programs. Because there is no centralized resource, FSSPs typically provide individualized in-house training and assign various aspects of the training duties to more experienced analysts, who often already have additional responsibilities that stem beyond casework. While larger FSSPs may have more formalized and robust training departments, dedicated training units are relatively rare due to limited resources (e.g., funding, staffing, time) and support. Consequently, FSSPs must divert attention from casework to attend to training needs, which creates pressures on FSSP management as well as senior and incoming analysts alike.

FSSP resources also impact access to external training and CE opportunities and professional credentialing programs such as certification. The decentralized nature of these critical functions results in wide variation among FSSPs. Furthermore, currently there is a duplication of efforts by various entities (e.g., individuals, FSSPs, accrediting bodies) on core concepts related to education, training, and professional credentialing efforts. While SDO standards are a positive start to minimize this duplication of efforts, these standards still allow for potential variability between FSSPs as there is allowance for FSSPs to determine if, and to what extent, they choose to implement these standards. At present, FSSPs have individualized requirements in place to either meet or exceed current accreditation requirements set by the FSSP's accreditation body and the FBI QAS.

To address variability in current DNA education and training in the United States, the EWG proposes development and funding of an NFDTC. A centralized location will provide a more universal foundation for the minimum KSA requirements. NFDTC-trained analysts should have the KSAs necessary to perform their tasks, troubleshoot issues that arise, and explain results in a coherent manner and in a variety of ways to end-users and factfinders.

The NFDTC would serve as a post-baccalaureate, multi-tiered training program designed to improve the quality and consistency of training from forensic biology screening to interpretation and expert witness testimony and help to improve the current gaps in DNA training, education, and professional credentialing in the United States by:

1. Providing standardized and centralized training and education, ensuring that all analysts receive the same level of foundational training and education regardless of their location.

2. Increasing access to training and education by advocating for better funding and resources for forensic DNA analysis.
3. Promoting diversity in the field by actively recruiting and training individuals from underrepresented groups (e.g., minority groups).
4. Supplying specialized training, including statistics, probabilistic genotyping, human factors, limitations of DNA technology and interpretation, communicating complex concepts, and understanding the legal system, to ensure that analysts have a strong foundational and practical understanding of these important aspects.
5. Providing CE and professional development opportunities to keep analysts up to date with the latest literature, technologies, techniques, and best practices.
6. Facilitating collaboration and networking among analysts through a platform for analysts to share information, collaborate, and network with their peers.
7. Bridging the gap between undergraduate or graduate coursework and the demands of forensic DNA casework.
8. Offering a harmonized assessment of an FSSP candidate's performance that would be consistent regardless of state or jurisdiction to help FSSPs successfully complete trial periods or exit unsuccessful applicants out of the system.
9. Engaging with external oversight bodies to expand current certification and licensure programs.
10. Training FSSP trainers to meet a set of standards set by the NFDTC or SDOs to ensure competent execution of effective evidence-based training techniques.
11. Assessing practical skills including the analyst's ability to obtain the correct answer or appropriate interpretation within an acceptable range on samples with ground-truth-known.
12. Providing a forum for considering the most challenging samples faced in casework and related suitability (for interpretation) considerations.
13. Being a source of feedback to a federal nonregulatory agency about samples that would be helpful for a federal nonregulatory agency to provide for research, training, and validation.
14. Sharing data and pedagogical techniques and resources between academic programs.
15. Offering a continuous feedback loop and updated information to FSSPs.
16. Acting as a source of feedback to existing academic programs about how to better prepare their students for participation in the NFDTC.

The NFDTC program would be available to individuals training to become or continue their training as DNA analysts, TLs, and quality personnel. By centralizing most of the training necessary for onboarding new FSSP personnel, FSSPs need only supplement with on-the-job training specific to the procedures used in the employing FSSP (e.g., the specific extraction procedure, use of the FSSP's Laboratory Information Management Systems [LIMS]) and the

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framework of the FSSP's quality management system (QMS) (e.g., working cases and writing reports with oversight from a mentor).

Recommendation 9.2: To reduce variability in education and training practices and increase quality and consistency of forensic DNA testing and interpretation, a federal nonregulatory agency or nonprofit organization should develop a National Forensic DNA Training Consortium with the mission to provide standardized and high-quality education and training for technical (e.g., DNA analysts, DNA Technical Leaders) and quality assurance personnel. This National Forensic DNA Training Consortium should offer the training needed for new forensic science service provider personnel as well as continuing education opportunities. Both offerings should include assessment components, written and practical as appropriate.

The calls for, and establishment of, national training programs is not a novel concept in forensic science. Furthermore, programs of this nature, even upon national recommendations for doing so, have failed to be developed or have been developed and are now defunct. Understanding why prior attempts to develop such programs have failed while others have succeeded will be helpful to successfully develop the NFDTC.[701]

9.6.1 Structure: Advisory Council

An oversight body, or Advisory Council, would preside over the NFDTC. This Advisory Council would consist of preeminent forensic DNA practitioners from various jurisdictional levels (i.e., small-scale to large-scale FSSPs), academics, professionals representing curriculum and professional development programs, forensic DNA researchers, human factors experts, members of SDOs, and other criminal justice partners (e.g., legal practitioners with diverse forensic experience). The NFDTC Advisory Council should also consist of SWGDAM and FBI representatives to ensure alignment between developed NFDTC curriculum and education and training requirements in the FBI QAS.

9.6.2 Function

Ideally, and subject to FSSP regulations, at the point of hire and prior to expiration of a probationary period, an incoming trainee would be supported by their FSSP to attend the NFDTC.

[701] Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF). Firearms-Related Training for Law Enforcement. ATF. Accessed March 26, 2024. https://www.atf.gov/careers/firearms-related-training-law-enforcement; Law Enforcement Innovation Center (LEIC). UT National Forensic Academy - 10 Week Program. Accessed March 26, 2024. https://leic.tennessee.edu/home/training/forensic-training/national-forensic-academy/; Virginia Commonwealth University (VCU) Department of Forensic Science. Forensic Firearms Identification Training. Accessed March 27, 2024. https://ocpe.vcu.edu/forensic-firearms-identification-training-certification-program/vcu.html.

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The trainee would be required to successfully complete their NFDTC course of study through a combination of written, oral, or practical skills assessments, thereby showing demonstrable competence in learned concepts prior to beginning in-house training. In-house training would then supplement the core concepts taught by the NFDTC by providing FSSP-specific training content necessary for the analyst to perform independent casework at that FSSP. Alternatively, an individual seeking employment could attend the NFDTC and complete the applicable training course(s) to market their proficiency in core concepts to potential employers.

9.6.3 Benefits

Developing the NFDTC as envisioned will provide significant benefits to the forensic DNA community and criminal justice partners. First, the NFDTC would reduce the need for FSSP management to divert analysts' time from casework for training purposes. Though some training will still be required in-house, much of the work in adequately preparing new analysts for casework can be accomplished through the NFDTC.

Having the NFDTC provide standardized initial training for all onboarding analysts will ensure that all analysts participating in this training program are receiving the same foundational KSAs and they are all assessed to the same degree. This standardization will decrease the variability within training programs between FSSPs and increase portability when personnel move between FSSPs. In addition, from a human factors perspective, having a third party involved in the evaluation of a candidate *before* they are fully integrated into the FSSP provides a much-needed independent perspective on the question of if the individual has the technical aptitude and capability to perform the duties of the position and is able to think critically in the ways that are needed for such a complex and rapidly changing area of forensic science.

9.6.4 Curriculum and Providers

The Advisory Council would present potential NFDTC training providers with a training outline as a minimum expectation for the topics and content of the curriculum. Potential training providers would be assessed on the extent to which their detailed curricula conform to these requirements and on their ability to deliver course content and assess trainees with fairness and rigor. The EWG envisions that potential training providers would be universities or other entities that meet the criteria highlighted in **Callout Box 9.2**. The Advisory Council should expand on this list of criteria.

Providers would also be expected to incorporate feedback loops with large-scale FSSPs with robust in-house training programs to ensure the proposed course material is fit for purpose. Those entities selected to be an NFDTC provider would be expected to work collaboratively to agree on a curriculum including student assessments that would be approved by the Advisory Council. The Advisory Council would be responsible for ensuring that the NFDTC provider

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network achieves geographic diversity and accessibility. Although much of this report focuses on autosomal STR DNA technologies and interpretation, centralized and standardized training in other technologies (e.g., Y-chromosome short tandem repeats [Y-STRs], next-generation sequencing) is equally important, and the EWG envisions the NFDTC expanding to cover these additional technologies.

Callout Box 9.2: NFDTC Provider Criteria

- Demonstrate existing capacity in forensic DNA or other relevant published research.
- Exhibit existing capacity in forensic DNA science application.
- Consist of faculty recognized as leaders in the forensic DNA field demonstrated through publications, presentations, and teaching.
- Possess appropriate facilities and instrumentation for hybrid (i.e., in-person and remote) training.
- Capable of meeting the curriculum requirements with faculty and staff who have direct experience and access to relevant instrumentation, interpretation methods, and software.
- Able to offer collaborations with law school faculty or other criminal justice partners for purposes of reporting, testimony, and legal disclosure training.
- Fit to develop and deliver curricula in the specific area of human factors in DNA analysis.

It is beyond the scope of the EWG to prescribe specific curriculum content. However, based on review of current practices discussed within this report and gaps between university curriculum and casework demands, the following high-level foundational topics/areas of focus should be considered, with the intricacies and specific content to be determined by providers and approved by the Advisory Council:

- Foundational forensic DNA analysis concepts
  - Collection/biological screening
  - Case assessment and interpretation model, the principles of interpretation, and the hierarchy of propositions
  - Complex mixture interpretation to include the challenges faced by FSSPs using probabilistic and manual methods
  - Statistics and population genetics
- Reporting of findings
- How to present complex topics in court
  - Courtroom proceedings and applicable rules relating to testimony
  - Trial preparation for providing expert testimony
  - Legal obligations (e.g., *Brady v. Maryland*, *Giglio v. United States*)
- Human factors, cognitive bias, and error

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  - Contextual information management
  - Interaction and communication with customers and criminal justice partners
- Accreditation standards (e.g., ISO/IEC 17025, FBI QAS)
- Quality assurance/quality control
  - Performing and evaluating validations
- Key topics, recommendations, and concepts discussed throughout this report

The Advisory Council would reserve the right to determine if a potential provider's curriculum includes sufficient elements from the course outline to conform to the curriculum requirements. This would include clear requirements with learning outcomes against which the student will be assessed as part of training program completion. It is critical that providers design their curricula so that students will be able to demonstrate the KSAs associated with the learning outcomes. Furthermore, the Advisory Council will have the authority to remove providers from the conformance list if they fail to adequately prepare trainees for competency assessments.

9.6.5 Funding

The Advisory Council will have discretion to determine funding. Ideally, existing federal funding could be directed to the NFDTC in the form of off-the-top DNA Capacity Enhancement for Backlog Reduction funds or Paul Coverdell Forensic Science Improvement Grants.[702] These funds may be used to support the costs associated with sending and supporting candidates through the program. Alternatively, funding could be secured from specific training and technical assistance funds through the Bureau of Justice Assistance or general support from the Department of Justice.[703]

Startup funding may be needed to support the work of the Advisory Council, and a federal nonregulatory agency or a nonprofit organization may be a good resource for initial program establishment and would be similar to the efforts made in establishing the ASCLD Leadership Academy.[704] The funding structure of the NFDTC should incentivize quality over quantity.

9.7 Criminal Justice Partner Education

Much like the education and training of forensic DNA analysts, the education and training of criminal justice partners is highly variable and localized, if available at all (see also ***Sec. 10.3.4*:**

[702] Bureau of Justice Assistance. Paul Coverdell Forensic Science Improvement Grants Program. Accessed March 26, 2024. https://bja.ojp.gov/program/coverdell/overview; Bureau of Justice Assistance. Training & Technical Assistance. Accessed March 26, 2024. https://bja.ojp.gov/training-technical-assistance.

[703] Bureau of Justice Assistance. Training & Technical Assistance. Accessed March 26, 2024. https://bja.ojp.gov/training-technical-assistance.

[704] The American Society of Crime Laboratory Directors (ASCLD). ASCLD Leadership Academy. Accessed March 23, 2024. https://www.ascld.org/ascld-leadership-academy/.

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Educating Parent Organization and Criminal Justice Partner Leadership). The United States currently has no centralized and accessible resource for training criminal justice partners on the wide array of forensic science concepts they are likely to encounter in criminal cases.[705] Under the current paradigm, training is mostly conducted by national- or state-level prosecutor, defense, or judicial training entities. There are a handful of programs that offer training across the board to all criminal justice partners, but it appears that none of the programs have a permanent funding source, and very few are focused specifically on forensic DNA analysis, much less human factors in DNA analysis.

For example, there is an effort underway at CSAFE to develop an accessible online platform called the Scientific Literacy Project with various bite-sized forensic science deliverables for criminal justice partners.[706] While not a replacement for the relationship building that occurs during local in-person events, it is intended to work alongside traditional programs by offering a convenient and universally accessible resource for criminal justice partners to stay informed about current issues in forensic science, with a specific section focused on forensic DNA analysis.

At the 75th Annual AAFS Scientific Conference, Jones and McLendon presented the results of a research project where they conducted a survey of how and where criminal justice partners[707] are trained on forensic science-related issues.[708] Based on the survey results, the authors recommended that criminal justice partners should receive training virtually when they need it, during local in-person events to build relationships, and by dual instructors to gain both scientific and legal perspectives, and that foundations of forensic science should be taught in law school.

High-quality and accessible training and education of criminal justice partners would help to improve just and fair outcomes in cases involving forensic DNA analysis. The transformative nature of criminal justice partner training initiatives is impossible to overstate. For this reason, the EWG supports efforts to develop, fund, and maintain high-quality and accessible training in this area so that legal practitioners, judges, and other criminal justice partners can perform their roles effectively. This education should include the following forensic DNA-specific content:

- A background on DNA –Transfer, Persistence, Prevalence, and Recovery including information on contamination, background DNA, and sample quality

[705] McLendon M, Jones II JP. What's Happening (or Not?) with Forensic Science Training for Officers of the Court. 75th Annual American Academy of Forensic Sciences Symposium, Orlando, FL 2023.

[706] Greiter BS, Renfro S, Carriquiry AL, Stern HS, Fabricant C, Meis M, Garcia L. The Scientific Literacy Project: A Collaborative Effort in Educating Legal Professionals on Forensic Evidence. 75th Annual American Academy of Forensic Sciences Symposium, Orlando, FL 2023. https://www.aafs.org/sites/default/files/media/documents/2023Proceedings_FINAL-june-1-23.pdf

[707] Legal practitioners, judges, law school professors, FSSP administrators, and scientists were interviewed to gain recommendations about what an ideal training program might look like in the future.

[708] McLendon M, Jones II JP. What's Happening (or Not?) with Forensic Science Training for Officers of the Court. 75th Annual American Academy of Forensic Sciences Symposium, Orlando, FL 2023.

- The importance of using tools like a case manager to reduce the impact of human factors in forensic DNA analysis
- Videos of analysts performing testing and interpretation processes
- The challenges of interpreting forensic DNA mixtures
- Considerations in assessing the suitability of forensic DNA profiles and existing inter-and intra-FSSP variability
- The administrative and technical review processes in forensic DNA analysis and examples of the types of issues (e.g., contamination, data interpretation errors, differences of opinion) this process is designed to address
- Historical areas of miscommunication in communication of forensic DNA results (e.g., the use of the term *inconclusive* in reporting and testimony)
- Understanding the likelihood ratio and the verbal scale (where used)
- Understanding the information contained in model discovery packets

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Appendix 9.1: The TFSC's Approach to Licensure

Since January 1, 2019, Texas has required forensic analysts and technicians to be licensed in the forensic disciplines of seized drugs, toxicology, forensic biology, firearms/toolmarks, and materials/trace.[709] Analysts and technicians become licensed by the TFSC.[710] The TFSC requires individuals seeking licensure to successfully complete the following requirements:[711]

1. Minimum education requirements[712]
2. Application fee
3. Successful completion of a General Forensic Analyst or Technician Licensing Examination
4. Specific coursework requirements[713]
5. Proficiency monitoring requirements

The law also required the TFSC to establish a Licensing Advisory Committee (LAC) to assist the TFSC in administering the program.[714] The LAC consists of nine individuals that serve staggered two-year terms. Each selected LAC must consist of seven forensic scientists from state, city, county, and private laboratories; one defense attorney; and one prosecutor that are recommended by their respective Texas-based professional association.[715] The LAC offers recommendations to the TFSC on all aspects of the licensing programs except for disciplinary actions.

The licensing requirement applies to a *forensic analyst*, defined by Texas law as an individual who, on behalf of an accredited FSSP, "technically reviews or performs a forensic analysis or draws conclusions from or interprets a forensic analysis for a court or crime laboratory."[716] *Forensic analysis* is defined by Texas law as "a medical, chemical, toxicologic, ballistic, or other expert

[709] Voluntary programs are also available or currently under development in the following disciplines: questioned documents, forensic anthropology, friction ridge, digital evidence, and crime scene.

[710] Texas Forensic Science Commission. Texas Forensic Science Commission Forensic Analyst Licensing Program. Accessed March 27, 2024. https://www.txcourts.gov/fsc/licensing/; Texas State Bill. *Texas State Bill No. 1287*. 2015. https://capitol.texas.gov/tlodocs/84R/billtext/pdf/SB01287F.pdf#navpanes=0.

[711] Texas Forensic Science Commission. Texas Forensic Science Commission Forensic Analyst Licensing Program. Accessed March 27, 2024. https://www.txcourts.gov/fsc/licensing/.

[712] An applicant for any Forensic Biology License category must have a baccalaureate or advanced degree in chemical, physical, or biological science which can be substituted with a forensic science degree from a FEPAC-accredited university. Additional rules presented in the Texas Administrative Code (TAC 651) address what specific science curricula must be included for the TFSC to accept a forensic science degree if it is not originating from a FEPAC-accredited university program.

[713] An applicant for a Forensic Biology/DNA Analyst License must demonstrate that they have fulfilled the specific requirements put forth by the FBI QAS. In addition to these requirements, an applicant must have a three-hour credit or equivalent in a statistics course from a FEPAC-accredited university or program approved by the TFSC.

[714] Texas State Bill. *Texas State Bill No. 1287*. 2015. https://capitol.texas.gov/tlodocs/84R/billtext/pdf/SB01287F.pdf#navpanes=0.

[715] Texas Forensic Science Commission. Texas Forensic Science Commission Forensic Analyst Licensing Program. Accessed March 27, 2024. https://www.txcourts.gov/fsc/licensing/.

[716] Texas Code of Criminal Procedure. *Chapter 38. Evidence in Criminal Actions. §38.01* 2021. https://statutes.capitol.texas.gov/docs/CR/htm/Cr.38.htm.

examination or test performed on physical evidence, including DNA evidence, for the purpose of determining the connection of the evidence to a criminal action."[717] The requirement applies regardless of whether the forensic analysis is performed for the state or the defense.[718] The licensure requirement applies to individual analysts who work in FSSPs outside of Texas but conduct forensic analysis in Texas cases because of outsourcing contracts or other similar circumstances.

The TFSC has also adopted administrative rules allowing for temporary licensure under certain exceptional circumstances, such as when a neighboring state's accredited FSSP performs forensic analysis for a Texas case due to the circumstances of a crime, but otherwise does not typically work on Texas cases. Forensic analysts working in federal FSSPs are deemed licensed under the Texas Administrative Code.

The General Forensic Analyst License is valid for a two-year period, during which the TFSC requires licensees to fulfill 32 hours of CE in compliance with OSAC Registry standard ASTM E2917-19a.[719] Of the required 32 hours of CE, a minimum of 16 hours must be obtained through "discipline-specific training, peer-reviewed journal articles, and/or conference education hours."[720] In addition, the TFSC requires all licensees to complete a TFSC-sponsored legal disclosure and professional responsibility refresher training course partnered with an embedded quiz before the expiration of the license cycle.

Central to Texas's licensing requirements is in-depth training on the intersection between science and the law and a demonstrated understanding of the roles and responsibilities of forensic scientists within the legal system. In other states, analysts may only receive cursory exposure to these topics, with most training focused primarily on foundational principles in biology, genetics, and statistics.

Effective May 16, 2018, the TFSC adopted a *Code of Professional Responsibility* for FSSP analysts, technicians, and management.[721] This Code was modeled in part after the National Commission on Forensic Science's *National Code of Ethics and Professional Responsibility for the Forensic*

[717] Texas Code of Criminal Procedure. *Chapter 39. Discovery. §39.14*. 2021. https://texas.public.law/statutes/tex._code_of_crim._proc._article_39.14.

[718] Individual consultants who are retained to critique and offer commentary on the testing performed by an accredited FSSP are not subject to the licensing requirement as *forensic analysts*. Rather, an individual's qualification as an 'expert' and the admissibility of related testimony is governed by applicable rules of evidence and related case law.

[719] ASTM International. *ASTM E2917-19a: Standard Practice for Forensic Science Practitioner Training, Continuing Education, and Professional Development Programs*. 2022. https://www.astm.org/e2917-19a.html.

[720] Texas Forensic Science Commission. Licensees. Accessed March 27, 2024. https://fsc.txcourts.gov/LicenseePublic.

[721] Texas Administrative Code: 37. *§651.219. Code of Professional Responsibility*. 2020. http://txrules.elaws.us/rule/title37_chapter651_sec.651.219.

Sciences.[722] However, it was modified to suit the needs of the Texas forensic science community. The most significant modification was the addition of a section setting forth expectations specific to FSSP management including requirements to encourage a quality-focused culture, provide opportunities for analysts to stay abreast of new scientific findings, and various requirements related to disclosure of nonconformances.[723]

As described in the Texas Administrative Code, the TFSC has the authority to discipline a licensee who commits professional misconduct or otherwise violates a rule or order of the TFSC.[724] The Texas Administrative Code defines professional misconduct as an instance in which "the forensic analyst or crime laboratory, through a material act or omission, deliberately failed to follow the standard of practice that an ordinary forensic analyst or crime laboratory would have followed, and the deliberate act or omission would substantially affect the integrity of the results of a forensic analysis. An act or omission was deliberate if the forensic analyst or crime laboratory was aware of and consciously disregarded an accepted standard of practice required for a forensic analysis."[725]

[722] National Commission on Forensic Science. *National Code of Ethics and Professional Responsibility for the Forensic Sciences*. n.d. https://www.justice.gov/usdoj-media/ncfs/media/898006/dl.

[723] Texas Administrative Code: 37. *§651.219. Code of Professional Responsibility*. 2020. http://txrules.elaws.us/rule/title37_chapter651_sec.651.219.

[724] Texas Administrative Code: 37. *§651.216. Disciplinary Action*. 2018. https://texreg.sos.state.tx.us/public/readtac$ext.TacPage?sl=T&app=9&p_dir=P&p_rloc=196522&p_tloc=&p_ploc=1&pg=7&p_tac=&ti=37&pt=15&ch=651&rl=216

[725] Ibid.

10. Management

10.1 Introduction and Scope

DNA analysts operate within a complex system of interacting components that influence task performance. This chapter discusses management and leadership's role in supporting DNA analysts to develop their expertise and adapt and respond to emerging methodologies, techniques, and technologies, all while managing their workload and working within organizational and managerial constraints.[726] Some of the recommendations contained within this chapter may seem aspirational for smaller forensic science service providers (FSSPs). In these instances, we note within the text how FSSPs with limited personnel or resources can still adapt to the spirit of the recommendations.

10.2 Personal and Professional Code of Ethics

Strong ethical principles, both personally and professionally, are at the foundation of any healthy FSSP.[727] Personal ethics relate to an individual's adopted or self-created values or code of conduct (e.g., morals and values). Professional ethics are values and principles introduced to an individual by a professional organization (e.g., confidentiality, objectivity, integrity, transparency, and proficiency).[728] Violation of or deviation from professional ethics can harm an analyst's professional status and tarnish the reputation of the organization and their colleagues or negatively impact work products.

FSSP leadership is responsible for establishing a clearly defined professional code of ethics that promotes the integrity of forensic scientists.[729] All individuals within the organization should have a clear understanding of its importance and meaning. FSSP leadership must consider this code when making decisions that will affect the organization and the individuals who may be impacted by the outcome.

DNA analysts must adhere to the FSSP's protocols, even if they conflict with their personal beliefs. For example, in FSSPs requiring the entry of arrestee DNA profiles into the Combined DNA Index System (CODIS), analysts must adhere to this protocol as a condition of employment, regardless of any personal objections. A strong sense of ethics within an FSSP can improve the organization's

[726] Expert Working Group on Human Factors in Latent Print Analysis. Latent Print Examination and Human Factors: Improving the Practice through a Systems Approach. National Institute of Standards and Technology; 2012. doi:10.6028/NIST.IR.7842

[727] Yadav PK. Ethical Issues across Different Fields of Forensic Science. *Egyptian Journal of Forensic Sciences*. 2017; 7(1):10. doi:10.1186/s41935-017-0010-1.

[728] Ibid.

[729] American Board of Criminalistics. *ABC Rules of Professional Conduct*. 2016. https://www.criminalistics.com/uploads/3/2/3/3/32334973/09-0001f_v1.0.1_abc_rules_of_professional_conduct.pdf.

productivity, foster camaraderie, improve adaptability, and facilitate decision-making and implementation processes.[730]

10.3 Leaders and Managers

Historically, scientific and technical fields have overlooked the importance of preparing individuals for managerial and leadership roles.[731] Those in leadership positions should encourage others to gain managerial experience, as both formal and informal leaders contribute to team performance. Developing necessary skills before assuming a leadership role is crucial for long-term team success. Investing time in individuals fosters vertical career growth, whether in people-oriented (leadership) or task-oriented (management) roles, promoting seamless leadership changes through effective succession planning.

10.3.1 Distinguishing Leadership from Management

Although commonly grouped together, there are differences between leaders and managers.[732] Recognizing and understanding the foundational differences between these two roles—while acknowledging their occasional overlap—can enhance FSSP efficiency. As Collins states, "for every hundred great managers, there is perhaps only one great leader."[733]

10.3.1.1 Leaders

Bison-Huckaby defines leaders based on their character, mindset, values, and guiding principles, emphasizing a people-oriented approach and a focus on human interaction rather than a formal title.[734] They are the type of individuals who tend to be natural role models, leading by example and motivating others. Additionally, Iacocca defines the "9 C's of leadership"[735] (communication, character, courage, conviction, charisma, competence, common sense, curiosity, and creativity) with a tenth aspect the ability to lead through a crisis.[736] These attributes encompass areas in which a leader should excel for effective organizational leadership.

[730] Yadav PK. Ethical Issues across Different Fields of Forensic Science. *Egyptian Journal of Forensic Sciences*. 2017; 7(1):10. doi:10.1186/s41935-017-0010-1.

[731] Collins J. *HR Management in the Forensic Science Laboratory: A 21st Century Approach to Effective Crime Lab Leadership*. Waltham: Academic Press: 2018. doi:10.106/C2013-0-19010-1.

[732] Information presented by Martina Bison-Huckaby to the Expert Working Group during a virtual meeting on 11/30/2020 – Presentation titled *Focus on Forensic Management Competencies Crucial for Successful Leadership.*

[733] Collins J. *HR Management in the Forensic Science Laboratory: A 21st Century Approach to Effective Crime Lab Leadership*. Waltham: Academic Press: 2018. doi:10.106/C2013-0-19010-1.

[734] Information presented by Martina Bison-Huckaby to the Expert Working Group during a virtual meeting on 11/30/2020 – Presentation titled *Focus on Forensic Management Competencies Crucial for Successful Leadership.*

[735] Iacocca L. *Where Have All the Leaders Gone?* Scribner: New York, NY, 2008.

[736] Yapp R. Lee Iaccoca - The 10cs of Leadership. Accessed May 19, 2023. https://www.leadershipforces.com/lee-iacocca-leadership/.

10.3.1.2 Managers

Although leaders are typically dedicated individuals who boost workplace morale, managerial positions are often more task-oriented, involving completing checklist items in daily operations. FSSP managers should possess various leadership competencies, and according to Bison-Huckaby, should be able to do the following:[737]

- Set or contribute to the FSSP's vision.
- Motivate, coach, and mentor employees.
- Foster and support team building.
- Maintain inter- and intra-organizational relationships.
- Communicate with external and internal collaborators.
- Promote trust and be active in conflict management.
- Use managerial skills such as project management, budgeting, and process improvement to contribute to the organization's strategic plan.
- Set goals and priorities.
- Analyze data to inform business decisions.
- Identify, address, and remedy mistakes to reduce the risk of reoccurrence.

10.3.1.3 FSSP Management and Leadership

Within an FSSP, there are typically two primary leadership and managerial positions: the DNA Technical Leader (TL) and the DNA **Administrative Supervisor**. The size and scope of the FSSP, including the number of personnel, caseload, and other factors will dictate the number of individuals dedicated to both administrative and technical responsibilities.

A TL should focus on the FSSP's technological vision, including the overall quality of the technology that the FSSP uses, their data interpretation methods, and the implementation and compliance with responsibilities as required by the Federal Bureau of Investigation's Quality Assurance Standards (FBI QAS).[738] An Administrative Supervisor should focus largely on case management, which includes budgeting, managing personnel, addressing the FSSP's backlog, and assessing the overall administrative quality of the final product (e.g., case report).

The TL must possess the technical skills (i.e., thorough knowledge of all aspects related to DNA processing and reporting) required to make sound decisions related to FSSP technology. FSSP

[737] Information presented by Martina Bison-Huckaby to the Expert Working Group during a virtual meeting on 11/30/2020 – Presentation titled *Focus on Forensic Management Competencies Crucial for Successful Leadership.*

[738] Federal Bureau of Investigation (FBI). *Quality Assurance Standards for Forensic DNA Testing Laboratories*. 2020. https://le.fbi.gov/file-repository/forensic-qas-070120.pdf/view.

management should provide TLs with the opportunity to establish and maintain their leadership skills, especially in FSSPs where TLs are not considered management personnel.

TLs often make decisions with widespread technical implications for the FSSP. Within the face of opposition, TLs must excel in conflict resolution and possess the skills to address disagreements. A proficient TL will be inherently adept at inspiring others through forward-thinking and innovation.[739]

While the FBI QAS requires a TL to possess a formal scientific background with a minimum of a master's degree in a biology-, chemistry-, or forensic science-related area to provide a working understanding of DNA analysis,[740] an Administrative Supervisor does not need this degree of scientific background. Nonetheless, the individual serving as the Administrative Supervisor must possess enough foundational forensic DNA knowledge to understand considerations relating to the workflow, budget, and personnel requirements of an FSSP.

FSSPs should employ both an Administrative Supervisor and a TL with sufficient skills and knowledge for the leadership and management of individuals. Skill acquisition can occur through internal or external training (see ***Sec. 9.3*: *Training***), involvement in continuing education (see ***Sec. 9.5*: *Continuing Education***), or engaged participation in relevant professional organizations.

Recommendation 10.1: In addition to the necessary technical qualifications, the DNA Technical Leader should have the knowledge, skills, and abilities to serve in a leadership capacity within the forensic science service provider. Parent organizations and forensic science service providers should continually support and dedicate resources (e.g., funding, time) to DNA Administrative Supervisors and DNA Technical Leaders to participate in managerial and leadership programs that further develop their leadership knowledge, skills, and abilities.

10.3.1.4 DNA Technical Leader and Administrative Supervisor Role Separation

In some FSSPs the TL and Administrative Supervisor roles are performed by the same person. Because both positions have different responsibilities and aims that require distinct skill sets, the EWG strongly advocates for these roles to be separated; a single individual should not assume both positions. Instead, at least two individuals should assume these positions, with consideration for agency size and available resources.

[739] Collins J. *HR Management in the Forensic Science Laboratory: A 21st Century Approach to Effective Crime Lab Leadership*. Waltham: Academic Press: 2018. doi:10.106/C2013-0-19010-1.

[740] Federal Bureau of Investigation (FBI). *Quality Assurance Standards for Forensic DNA Testing Laboratories*. 2020. https://le.fbi.gov/file-repository/forensic-qas-070120.pdf/view. Standard 5.2.1.

When these roles are not separated, the individual serving as both the Administrative Supervisor and TL may become overworked and overinvolved in the decisions impacting the operations and functions of the FSSP. Including a TL in discussions regarding personnel issues that are not inherently technical in cause or nature may impact the TL's ability to make decisions purely based on the technical issues at hand.

For the successful separation of roles, it is crucial to clearly define and allocate the duties, responsibilities, and authorities that the TL and the Administrative Supervisor hold. This clarity enhances workflow efficiency and division of labor. Defining which individual will oversee each aspect of an FSSP's functionality before they assume the position will eliminate confusion about which individual has primary responsibility over each feature, thereby mitigating any potential instances of role discordance. This clear separation of function, particularly the reporting structures, should be formally communicated (e.g., via written memorandum or formal policy) to all FSSP personnel and other relevant criminal justice partners and collaborators who interact with the individuals in these positions.

The EWG acknowledges that separating these roles between at least two individuals may be difficult in some FSSPs. FSSP size, limited financial and personnel resources, and other uncontrollable factors could hinder this in practice. Despite these limitations, FSSPs should make every effort to separate these positions because of the foundational differences in responsibilities and the importance of creating a separation of power to prevent a single individual from controlling all decisions made within the organization. The TL and Administrative Supervisor should report to a department head or director rather than to each other. If one individual does have to fulfill both positions, it is critical that FSSP management provide this individual with the necessary leadership and managerial skills to successfully perform the responsibilities of both the TL and Administrative Supervisor.

Recommendation 10.2: Forensic science service provider management should clearly define the roles, responsibilities, and authorities of DNA Administrative Supervisor and DNA Technical Leader positions. Management should dedicate leadership resources to each role and communicate the definition of these roles to all individuals who are employed by, or work closely with, the forensic science service provider to help clarify reporting structures and enable the individuals to fulfill their responsibilities. Ideally, because of the difference in responsibilities between DNA Administrative Supervisors and DNA Technical Leaders, different individuals should hold these positions.

This publication is available free of charge from: https://doi.org/10.6028/NIST.IR.8503

10.3.2 Educating Managers and Developing Leaders

One criticism of the forensic science community is that while its leaders and managers possess technical training, they often lack formal managerial and business training.[741] Pyrek created "The Dirty Dozen," which is a list of common charges leveled across FSSPs.[742] One of these charges is a lack of management in FSSPs.[743] The 2009 National Academy of Sciences (NAS) Report noted the need for specific kinds of management training, quoting a 1999 National Institute of Justice (NIJ) Report[744] which stated that, "...managers need training in fiscal management, quality systems management, leadership, project management, human resource management, and customer service."[745] Although a decade of change and development separate the quoted report and the publication of the 2009 NAS Report, the latter report still noted the continuing need for the kind of training identified in 1999.

Historically, training in FSSPs focused on discipline-specific courses, with analysts attending schools focusing on the proper analysis of DNA recovered from crime scenes. DNA analysis training curricula lack content related to managing an FSSP or acting as a supervisor in a specific section. Traditionally, the most productive or senior analysts were promoted to supervisor because of their skill at the workbench or years of service and not their ability to lead, creating a gap in management skills that additional training may resolve.

Positive improvements in the field of FSSP management training have occurred since the 2009 NAS Report. Many forensic science professionals received extensive training in FSSP management through the West Virginia University Forensic Management Academy[746] and the University of California-Davis Forensic Science Leadership and Management Program. These programs no longer exist, however, in 2014 ASCLD developed the ASCLD Leadership Academy to promote forensic management and more specifically leadership training in forensic science.

[741] International Symposium on Human Identification (ISHI) News. The Importance of Leadership Training in the Forensic Field. Accessed March 27, 2024. https://www.ishinews.com/the-importance-of-leadership-training-in-the-forensic-field/.

[742] Pyrek KM. *Forensic Science Under Siege: The Challenges of Forensic Laboratories and the Medico-Legal Death Investigation System*. Elsevier / Academic Press: Amsterdam, Netherlands, 2007.

[743] Ibid.

[744] National Institute of Justice (NIJ). *Forensic Sciences: Review of Status and Needs*. 1999. 94-IJ-R-004. https://www.ojp.gov/pdffiles1/173412.pdf.

[745] National Research Council, Committee on Identifying the Needs of the Forensic Science Community. *Strengthening Forensic Science in the United States: A Path Forward*. The National Academies Press: Washington, DC, 2009. doi:10.21428/cb6ab371.b2d683d2. p. 232.

[746] West Virginia University. WVU Center for Executive Education Helping to Connect Forensic Science and Business. Lab Manager. Accessed March 27, 2024. https://www.labmanager.com/news/wvu-center-for-executive-education-helping-to-connect-forensic-science-and-business-4925.

The ASCLD Leadership Academy is a three-level training program developed for current and future FSSP leaders. The Academy designed the curriculum to deliver the highest-quality training focusing on the following topics:[747]

- Leadership
  - Leadership styles and theories
  - Transitioning from peer to supervisor
  - Conflict management
  - Ethics and self-management
  - Cultural change
- Leadership communication
  - Communication styles and skills
  - Personality
  - Team building, engagement, and motivation
  - Cross-cultural communication
  - Communication as a leadership tool to solve FSSP issues
- FSSP operations
  - Strategic management
  - Process and performance management
  - Quality management, human resources, and financial management
  - Customer and collaborator management

Since its inception, over 1000 forensic science professionals have attended the Academy.[748] Attendees have included individuals from across the United States and internationally. Through this training, personnel from various forensic science disciplines have gained leadership and management skills that help equip them to manage their FSSPs more effectively and to meet the challenges faced by FSSPs. Once a student has completed all three levels, they will have 120 contact hours dedicated toward FSSP-specific leadership training.[749]

[747] The American Society of Crime Laboratory Directors (ASCLD). ASCLD Leadership Academy. Accessed March 23, 2024. https://www.ascld.org/ascld-leadership-academy/.

[748] Ibid.

[749] Ibid.

10.3.3 Certifying Forensic Managers

The field of forensic science is no stranger to certification programs. The American Board of Criminalistics (ABC),[750] International Association for Identification (IAI),[751] and Association of Firearm and Tool Mark Examiners (AFTE)[752] are just some of the programs that provide certifications within the forensic science community (see ***Sec. 9.4.1*: Professional Certification).** However, these certification bodies focus on the analytical aspects of forensic science and not FSSP management.

Recognizing a need for a robust certification program for FSSP professionals that focuses on management and leadership, the Arnold Foundation awarded RTI International a grant to develop such a certification in 2015.[753] In partnership with ASCLD, RTI International developed the Forensic Manager Certification Program (FMCP).[754] The FMCP is the first body in the United States to certify FSSP leaders in FSSP management. This program:[755]

> [P]rovides criteria to training and education providers that cover a comprehensive, consensus-based curriculum to prepare forensic scientists to become leaders. FMCP designed the training for forensic science professionals aspiring to be leaders within their laboratories, unit supervisors, managers, executives in public laboratories, and units within police agencies or commercial laboratories. By requiring providers to maintain a specific level of topical coverage, the FMCP targets the students who finish those programs, offering them an opportunity to achieve professional certification in addition to completing the required training.

The FMCP consists of three levels of certification for Certified Forensic Managers (CFM): supervisors (CFM-I), managers (CFM-II), and executives/directors (CFM-III).[756] Each certification level is a prerequisite for the next; CFM-applicants must already be certified as a CFM-I, regardless of their job title or previous experience in management positions.

Although the ASCLD Leadership Academy is the first approved program provider where successful completion of the program allows the student to take the FMCP certification examination, the goal of the FMCP is to have several academic institutions approved as providers offering all three levels of certification. In addition, the ASCLD Leadership Academy developed a

[750] American Board of Criminalistics. Certification. Accessed March 23, 2024. https://www.criminalistics.com/certification.html.

[751] International Association for Identification. Certifications. Accessed March 27, 2024. https://www.theiai.org/certifications.php.

[752] Association of Firearm and Tool Mark Examiners (AFTE). AFTE Certification. Accessed March 23, 2024. https://afte.org/afte-certification.

[753] The American Society of Crime Laboratory Directors (ASCLD). *Executive Education Digest: A Leadership Development Resource for Forensic Science Laboratory Directors and Managers*. Vol. 5. 2016. https://www.ascld.org/wp-content/uploads/2016/04/2016-ASCLD-Executive-Education-Digest.pdf.

[754] RTI International. Certified Forensic Manager. Accessed May 22, 2023. https://forensicrti.org/fmcp/cfm-overview/.

[755] Ibid.

[756] Ibid.

bridge course, allowing graduates of the West Virginia University Forensic Management Academy and the University of California-Davis Forensic Science Leadership and Management Program to meet the curriculum eligibility requirements to take the CFM-I certification.

Although there are other avenues to receive management and leadership training, the ASCLD Leadership Academy and FMCP serve as two ways in which Administrative Supervisors and TLs can receive FSSP-specific management training. As FMCP approves more providers, it will become more easily accessible to FSSP leadership personnel. These programs will help develop leadership skills and management techniques to augment analysts' technical training and knowledge to pursue a leadership position.

Parent organizations and FSSPs typically fund the necessary training for analysts to remain scientifically proficient; however, these entities must understand that leadership training is a critical element in developing sound practices within an FSSP. As such, additional resources (e.g., funding, time) should also be allocated by parent organizations to continually support leadership training for Administrative Supervisors and TLs.

10.3.4 Educating Parent Organization and Criminal Justice Partner Leadership

The EWG further recommends that parent organization and criminal justice partner leadership attend training programs that include guidance for FSSPs on best practices and professional standards (see also ***Sec. 9.7*: *Criminal Justice Partner Education***). The FBI's National Academy is one of the premier training grounds for executive and mid-level leadership in law enforcement. This program offers a wide range of coursework over 10 weeks and is designed to develop leaders in law enforcement and improve the administration of justice by raising law enforcement standards across the United States and internationally.[757] Courses include "intelligence theory, terrorism and terrorist mindsets, management science, law, behavioral science, law enforcement communication, and forensic science."[758]

Although the FBI National Academy lists forensic science in the curriculum, the primary focus of this curriculum is the structure and proper use of the FBI Crime Laboratory. The course provides an overview of forensic science and an in-depth view of the applications and benefits of using the FBI Crime Laboratory and the FBI Evidence Response Team, but it does not focus on elements affecting the management of an FSSP.

Although this is a valuable course, the FBI National Academy and other law enforcement executive trainings should develop additional curricula that focus on the importance of accreditation, laboratory independence, bias, undue influence, laboratory operations, laboratory

[757] Federal Bureau of Investigation (FBI). FBI Services: Training Academy. Accessed March 27, 2024. https://le.fbi.gov/training.

[758] Ibid.

leadership, scientific limitations, principles of interpretation, and quality systems. In addition to strengthening communication between parent organization and FSSP leadership, these curricula would provide parent organization leadership better insight into where and why funding should be allocated to improve FSSP operation and the bounds of the scientific capabilities of the FSSP they oversee.

Most FSSPs fall under the command of a law enforcement agency at the local, state, or federal levels, and some fall under the oversight of a prosecutor's office, medical examiner's/coroner's office, or other entity.[759] The executive leadership of these FSSPs should also receive training in these additional curriculum components to ensure a uniform understanding of the FSSP's essential needs and the proper use of its personnel. Parent organization leadership and criminal justice partners should undertake this training regularly to keep up with changes to FSSP policies and technological advancements. Some topics may require annual training, while others require training only as policies change.

Recommendation 10.3: Parent organization leadership and criminal justice partners who regularly interact with the forensic science service provider should understand laboratory best practices in order to accurately represent the scientific evidence and capabilities of the laboratory, reduce the risk of the parent organizations or criminal justice partners exerting undue influence on DNA analysts, and appropriately allocate funding and resources for forensic science service provider operations. To inform this understanding, forensic science service providers should offer regular training to parent organization leadership and criminal justice partners on the following topics:

- **Quality systems**
- **Accreditation**
- **Undue influence**
- **Scientific limitations**
- **Laboratory reports**
- **Laboratory operations**
- **Laboratory leadership**
- **Laboratory independence**
- **Principles of interpretation**
- **Changes to laboratory practices**
- **Cognitive bias and contextual information management procedures**

[759] Durose MR, Walsh KA, Burch AM. *Census of Publicly Funded Forensic Crime Laboratories, 2009*. United States Department of Justice. 2009. https://bjs.ojp.gov/content/pub/pdf/cpffcl09.pdf.

10.3.5 Professional Development and Promotion

Another key component of leadership is personnel development. FSSPs have historically struggled with managers in technologically or scientifically based fields being promoted into upper management because of their specific technical skills rather than their leadership skills.[760] There has been a recent push to shift the focus solely from technical skills to include leadership skills among FSSP leaders.

Collins proposes an approach to professional development that includes looking for and developing characteristics in employees, called guideposts (**Table 10.1**). Different guideposts become more relevant and critical at each level of accountability within the FSSP. FSSP leadership should assign employees to a role that fits their identified individual strengths.

Table 10.1: Eight guideposts to look for and develop in employees

Levels of Accountability	Role	Guideposts
Pre-professional	Learn	Coachable
		Competent
Professional	Perform laboratory work	Engaged
		Trustworthy
Managerial	Manage laboratory work	Discerning
		Influential
Executive	Manage laboratory strategy	Visionary
		Strategic

Table based on John Collins' presentation to the EWG and approved for use by John Collins.[761]

Collins also advocates for leadership positioning as opposed to succession planning.[762] Leadership positioning aims to develop employees from the onset to prepare them for an opening for a leadership position within the FSSP. If done successfully, there will then be multiple employees who possess the requirements necessary to fill the position. Leadership positioning also helps ensure that the FSSP has trusted leaders who believe they can serve the organization, rather than entitled leaders who believe that a promotion is a reward for their previous work. There are four components to leadership positioning:[763]

[760] Becker WS, Dale WM, Pavur EJ. Forensic Science in Transition: Critical Leadership Challenges. *Forensic Science Policy & Management: An International Journal*. 2010; 1(4):214-23. doi:10.1080/19409044.2010.508507.

[761] Information presented by John Collins to the Expert Working Group during a virtual meeting on 12/07/2020.

[762] Information presented by John Collins to the Expert Working Group during a virtual meeting on 12/07/2020.

[763] Collins J. *HR Management in the Forensic Science Laboratory: A 21st Century Approach to Effective Crime Lab Leadership*. Waltham: Academic Press: 2018. doi:10.106/C2013-0-19010-1.

1. Ensure every employee is supplied opportunities to develop as a leader.
2. Develop individual effectiveness at their respective level.
3. Model leadership behaviors.
4. Provide an option for employees who do not want to pursue a manager track that still allows them to grow levels of responsibility.

As discussed in ***Sec. 10.3.2*: *Educating Managers and Developing Leaders***, there are several opportunities to provide current and future FSSP leaders with leadership training. Senior management should ensure that those promoted to leadership positions within the FSSP have the appropriate foundational training and are provided with the necessary resources to assume those roles.

10.3.6 FSSP Leadership and Management Challenges

FSSP management faces a range of organizational challenges, including budget management, productivity, efficiency, personnel management, and customer satisfaction (see **Table 10.2**). Like other scientific organizations, FSSP management deals with issues such as specialized instrumentation and training, rapid technological advancements, and accreditation. However, FSSPs operating under law enforcement agencies encounter unique challenges. Law enforcement organizations tend to have sworn personnel who operate under a command-and-control structure, which is characterized by an avoidance of risk-taking behaviors and tends to result in changes to policies and procedures advancing slowly. FSSPs, however, tend to comprise civilian personnel with advanced degrees. These civilian-led organizations encourage a culture of continuous advancement and improvement. These differences in core management philosophies can result in additional testing and analysis process constraints. For example, forensic scientists are in the difficult position of receiving pressure for quicker turnaround, especially regarding sexual assault kit (SAK) backlogs and legislation[764] requiring more cases to be tested on a strict timeline, within a context of zero error tolerance.

Table 10.2: Common challenges faced by FSSP leadership and management

Common Leadership and Management Challenges in an FSSP	
• Identification of qualified candidates for positions	• Addressing the problem of less effective employees
• Balancing backlog reduction with supervision of new employees	• Handling employees who failed to make it through training
• External communications with criminal justice partners	• Balancing backlog reduction with ongoing investigation support
• Retention of personnel	

[764] New York State Senate. *Senate Bill S8117*. 2016. Accessed March 27, 2024. https://www.nysenate.gov/legislation/bills/2015/S8117.

This publication is available free of charge from: https://doi.org/10.6028/NIST.IR.8503

Common Leadership and Management Challenges in an FSSP	
• Timely completion of training responsibilities • Competitive salaries for disciplines • Motivating employees • Generational differences • Sense of entitlement among employees • Providing incentives for top performers • FSSP succession planning • Sworn versus civilian cultural differences • Funding new technology and systems • Using performance appraisals effectively • Education requirements	• Support for sending FSSP personnel to training programs, especially those off-site or out-of-state • Command-and-control management style • Having time for scientific research • Cost-cutting/personnel reduction • Workload increase • Working with labor representatives • Error management • Quality and quantity performance issues • Onboarding process of new personnel • Workforce freeze or reduction • Meeting demands of the criminal justice system

Table originally appeared in Becker et al, 2010[765] and adapted with permission.

10.4 Organizational Management

DNA Administrative Supervisors, TLs, and other FSSP management (all are referred to throughout this section as *FSSP leaders*) are responsible for ensuring the successful operation of a complex scientific and business operation involving highly trained and educated professionals. The world of business administration has organizational management principles these leaders can leverage to succeed, including strategic management, process improvement, human resource management, quality management, and criminal justice partner management.

Strategic vision, planning, and management are foundational principles that align with operations to achieve the organization's mission and vision. Strategic management is an iterative process that includes an assessment of current operations, the formulation of strategies to achieve the mission, the implementation of developed strategies, an evaluation of those strategies, and corresponding adjustments to improve effectiveness.[766] This process, as shown in **Fig. 10.1**, is cyclical and continues on a regular and routine basis.

[765] Becker WS, Dale WM, Pavur EJ. Forensic Science in Transition: Critical Leadership Challenges. *Forensic Science Policy & Management: An International Journal*. 2010; 1(4):214-23. doi:10.1080/19409044.2010.508507.

[766] Newman J, Dawley D, Speaker PJ. Strategic Management of Forensic Laboratory Resources: From Project FORESIGHT Metrics to the Development of Action Plans. *Forensic Science Policy & Management: An International Journal*. 2011; 2(4):164-74. doi:10.1080/19409044.2012.693571.

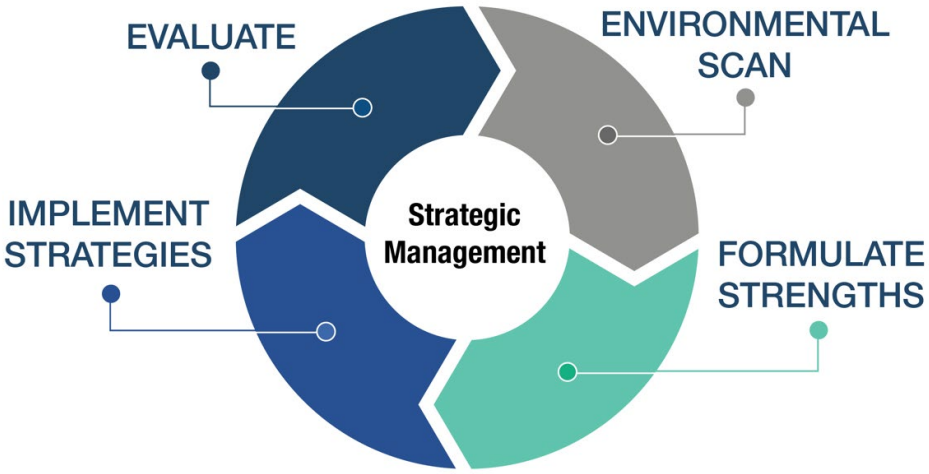

Figure 10.1: The strategic management cyclical process.

Figure originally appeared Newman et al, 2012[767] and adapted with permission.

FSSP leaders are responsible for crafting a strategic plan with input from all levels of the organization. While each FSSP's strategic plan may vary, each includes elements such as the mission and vision statement, roles and responsibilities of individuals assigned to achieve set goals, and metrics to track goal achievement progress. All FSSP personnel are responsible for executing the strategic plan.

Often, an organization's overall mission is determined by the parent organization, but it is important that it is achievable and consumable for the FSSP and its personnel. The mission should answer the questions: "Why do we do what we do?" and "Why is it important?"[768] This becomes an everyday mindset, which focuses efforts and aligns goals across the organization.

The processes FSSPs use can be incredibly complex, with ever-evolving technological advancements. A sampling of business tools that can be used to aid in these process improvement efforts include Balanced Scorecarding, Lean Six Sigma, Process Mapping, and Root Cause Analysis.[769] Using these tools requires leaders to be well-versed in project management, change management, and process improvement. Direct-to-DNA or Y-screening is a good example

[767] Ibid.

[768] Sinek S. *Start with Why: How Great Leaders Inspire Everyone to Take Action*. Portfolio: New York, NY, 2009. doi:10.1037/e515802011-001.

[769] Damelio R. *The Basics of Process Mapping*. 2nd ed. CRC Press: New York, NY, 2011. ; Harrington HJ. *Business Process Improvement: The Breakthrough Strategy for Total Quality, Productivity, and Competitiveness*. McGraw Hill: New York, NY, 1991. ; Houck M, Speaker PJ, Fleming AS, Riley RA, Jr. The Balanced Scorecard: Sustainable Performance Assessment for Forensic Laboratories. *Science & Justice*. 2012; 52(4):209-16. doi:10.1016/j.scijus.2012.05.006; Ikumapayi OM, Akinlabi ET, Mwema FM, Ogbonna OS. Six Sigma Versus Lean Manufacturing - An Overview. *Materials Today: Proceedings*. 2020; 26:3275-81. doi:10.1016/j.matpr.2020.02.986; Speaker PJ. Process Improvement and the Efficient Frontier: Forecasting the Limits to Strategic Change across Crime Laboratory Areas of Investigation. *Forensic Science Policy & Management: An International Journal*. 2017; 8(3-4):109-27. doi:10.1080/19409044.2017.1387204.

of a technique that has been incorporated into many FSSPs. This technique has in many cases improved the effectiveness and efficiencies in FSSPs, especially relating to the processing of SAKs and remedying backlogs.[770]

In many FSSPs, leaders are responsible for making hiring decisions, onboarding, training personnel, managing performance, and handling matters of discipline. As such, human resource management is another foundational business function in which FSSP leaders must be well-versed. FSSP leaders must have a program for performance management that includes intentional and routine processes that align with an organization's mission, are constructive for improved performance, allow for employee input, and support employee development and career planning.[771]

Workforce and succession planning are critical to the continued success of FSSP operations (see ***Sec. 10.3.5: Professional Development and Promotion***). This planning includes identifying current and future needs, ensuring personnel are well-positioned to succeed as planned and unplanned attrition occurs, and providing career development to enable personnel to succeed as they assume critical roles, particularly the TL and Administrative Supervisor positions.

Another critical function of FSSP leaders is their role in supporting and managing the quality system. Leaders are highly visible in the FSSP and set the tone for culture and expectations for quality and productivity levels (see ***Sec. 10.6: Shaping FSSP Culture***). The critical role that leaders play in managing quality at different levels of the organization cannot be overstated. It is important that there is deliberate thought incorporated into the organizational management of the FSSP related to balancing the quality and quantity of the work product and output in a manner that is non-punitive and supports the organization's mission. This requires leaders to be actively engaged in the quality system with a positive and constructive approach that holds quality in high regard on a daily basis. This manifests in activities such as routine personnel meetings and operational processes that are focused on quality (e.g., blind proficiency testing or reexaminations, quality system responsibilities, performance expectations, a code of conduct).

10.4.1 Criminal Justice Partner Management

The business approaches discussed previously in this section focus on internal operations; however, another important facet of organizational management is criminal justice partner management. Criminal justice partners include members of the criminal justice community (law enforcement, prosecutors, defense attorneys, and judges) and the other members of the

[770] Scientific Working Group on DNA Analysis Methods (SWGDAM). *Report on Y-Screening of Sexual Assault Evidence Kits (SAEKs)*. 2020. https://www.swgdam.org/_files/ugd/4344b0_e8334cb799704a1dabbd8d41f58b979d.pdf.

[771] Collins J. *HR Management in the Forensic Science Laboratory: A 21st Century Approach to Effective Crime Lab Leadership*. Waltham: Academic Press: 2018. doi:10.106/C2013-0-19010-1.

community impacted by the work produced by an FSSP. There are many different types of information that FSSP leaders can access to familiarize themselves with their criminal justice partners and understand the interactions they have with those entities and persons. Some options for gathering this information include surveys, feedback tools, meetings, complaints, and preventative and corrective actions.

Leaders have a responsibility to understand the experience that criminal justice partners have when engaging with them. This requires that leaders have an appreciation for the relationships their organization has with criminal justice partners, the influence this relationship has on FSSP personnel, and opportunities for improvement presented to the FSSP through this relationship. Factors to consider include the influence of task-irrelevant information, case management and case acceptance practices, criminal justice partner training, reporting, and discovery and public information requests. FSSP leaders need to support the design of processes that are responsive to the criminal justice system's needs with a focus on quality operations that emphasize transparency.

Recommendation 10.4: DNA Administrative Supervisors and DNA Technical Leaders manage complex scientific and business operations. To continually improve the organization's performance, these leaders should actively engage in essential business practices of operational management, including strategic planning, process improvements, human resource management, succession planning, quality management, and criminal justice partnerships.

10.5 Institutional Structure

The 2009 NAS Report recommended that FSSPs should be separated from the administrative control of law enforcement and prosecutorial agencies to support an independent resource to the criminal justice system.[772] Since the publication of that report, several FSSPs, such as the Houston Forensic Science Center (HFSC), have achieved this independent structure.[773] Private FSSPs are also independent of the administrative control of law enforcement and prosecutorial offices. However, this independent structure has not prevented scandal or catastrophic failure, as in the case of the D.C. Department of Forensic Sciences, which has had an unfortunate history of systemic failures.[774] Additionally, these failures go beyond the organizational structure to

[772] National Research Council, Committee on Identifying the Needs of the Forensic Science Community. *Strengthening Forensic Science in the United States: A Path Forward*. The National Academies Press: Washington, DC, 2009. doi:10.21428/cb6ab371.b2d683d2.

[773] Houston Forensic Science Center. Record Search. Accessed March 27, 2024. https://records.hfscdiscovery.org/.

[774] SNA International. *DC Department of Forensic Sciences Laboratory Assessment Report*. 2021. https://dfs.dc.gov/sites/default/files/dc/sites/dfs/publication/attachments/DFS%20Forensic%20Laboratory%20Assessment%20Report.pdf.

systemic issues that independent structure, third-party oversight, and accreditation were unable to prevent.[775]

Understanding the importance of independence extends beyond organizational structure and is highly dependent on the systems, policies, and practices in place that mitigate and limit the undue influence that being organizationally placed within a law enforcement or prosecutorial agency may have on an FSSP and forensic scientists. For example, private FSSPs often face some of the same pressures that public FSSPs do, in part because they often serve many of the same customers. The National Sexual Assault Kit Initiative (SAKI),[776] for example, resulted in tens of thousands of SAKs being sent to private FSSPs by law enforcement and prosecutorial agencies. Thus, the opportunity for undue influence to adversely impact an FSSP can also exist for private FSSPs just as it does for public FSSPs. As a result, independent organizational structure alone does not fully circumvent the impact these relationships can have on the operations of FSSPs.

It is critically important that systemic measures are taken to support the independence and autonomy of FSSPs that go beyond removing these institutions from the administrative control of law enforcement and prosecutorial agencies. These measures include individual, organizational, and quality measures focused on supporting the objective use of science in the criminal justice system regardless of the entity or individual requesting the analysis. Measures to achieving FSSP independence and autonomy include:

- Leadership engagement
- Risk management
- Awareness and understanding
- Policy and practice
- Transparency
- Organizational culture

10.5.1 Leadership Engagement

Having an independent and autonomous FSSP begins with FSSP leaders. They play a pivotal role in the development of the organizational culture and the core value of FSSP autonomy and independence. The concepts of autonomy and independence need to be embedded in the quality system, which provides the structure in which all tasks and activities are completed. Leaders need

[775] Ibid.

[776] Funded by the Bureau of Justice Assistance to support community response to sexual assault in a victim-centered and trauma-informed manner.

to provide resources to develop systems, policies, and practices that support autonomy and independence.

Employee empowerment and accountability are also key components and ensure employees have permission to act in support of this core value. FSSP leadership should support a transparent operation both internally and externally because this provides access and accountability to decision-making and FSSP operations. FSSP leaders have a responsibility to be the first and last guard in support of independence and autonomy of the FSSP and their teams.

10.5.2 Risk Management

A way for FSSPs to understand the potential impact of institutional structure reformation on the relationship between the customer or criminal justice partner and the FSSP is to conduct a risk management analysis of the FSSP operations with a specific focus on autonomy and independence. It is important to understand the potential failure points in the FSSP's systems that are subject to undue influence on scientific decisions and FSSP operations. This can be achieved by establishing a working group that identifies the failure points, examines the interconnectivity of the systems, and then recommends measures to mitigate these risks.[777] This should be a cyclical process during which the impact of mitigation measures is evaluated alongside the determination of new or changed risks.

10.5.3 Awareness and Understanding of Cognitive Bias

Cognitive bias is a significant focus of research,[778] and understanding its impact has played a pivotal role in the improvement of forensic science (see ***Sec. 2.4*: *Cognitive Bias***). However, it is imperative that additional research on the impacts of bias on forensic scientists and FSSPs continues. Increased awareness of cognitive bias within FSSPs starts with incorporation of this topic into employee onboarding, continuing education, and training of FSSP personnel. These programs should occur on an ongoing basis and include information covering the role of forensic science in the criminal justice system, bias and its impact, ethics, quality system measures addressing bias, and mitigation measures implemented in the FSSP.

Increased employee awareness alone, however, is not sufficient to mitigate bias and undue influence. FSSPs must also assist forensic scientists in developing skills to mitigate their effects. FSSPs should strive to create an environment that recognizes and values a diversity of views, including dissenting ones, as a way to "check" not just individual biases but organizational ones.

[777] Camilleri A, Abarno D, Bird C, Coxon A, Mitchell N, Redman K, Sly N, Wills S, Silenieks E, Simpson E, Lindsay H. A Risk-Based Approach to Cognitive Bias in Forensic Science. *Science & Justice*. 2019; 59(5):533-43. doi:10.1016/j.scijus.2019.04.003.

[778] Cooper GS, Meterko V. Cognitive Bias Research in Forensic Science: A Systematic Review. *Forensic Science International*. 2019; 297:35-46. doi:10.1016/j.forsciint.2019.01.016.

Forensic scientists should be empowered and supported to alert both FSSP management and criminal justice partners of instances of suspected or perceived undue influence.

Measures to mitigate the risks of cognitive bias must be incorporated into FSSP policies and practices. This starts with a quality system that supports the FSSP's work product. Measures that have been incorporated into FSSP systems include context manager models and linear sequential unmasking (see ***Sec. 3.3.4*: *Contextual Information Management***). These processes ultimately support the goal of limiting task-irrelevant information. Some case information is necessary to formulate propositions and triage cases; however, the individual accessing this information does not need to be the same analyst who performs the technical or interpretation tasks. Separating these tasks can be a measure to help mitigate bias.

It is necessary that a comprehensive approach is taken to achieve autonomy and independence and that all FSSP personnel vigilantly support this culture and all that it entails. See **Callout Box 10.1** for an example of the Phoenix Police Department's case management procedure.

Callout Box 10.1: Case Management

The Phoenix Police Department uses a cooperative approach to forensic analysis between the detective bureaus, its Crime Lab, and the Maricopa County Attorney's Office to manage the cases that are submitted to the laboratory for analysis. The goal is to work together to provide investigative information to resolve cases and prepare for trials as efficiently and effectively as possible while recognizing and respecting the autonomy of each group.

The Crime Lab implemented two policies to facilitate this process and partnerships: the Evidence Acceptance policy and the Case Evaluation policy. In addition to these policies, the Crime Lab has a detective and two civilian investigators assigned to the laboratory to act as a liaison between the detective bureaus and the county attorney's office.

The Evidence Acceptance policy places limits on the number and types of items that can be submitted based on the crime type, while also stating that the Crime Lab will only process the most probative evidence initially. For example, homicide cases are allowed ten items for DNA per round of processing, while property crimes are permitted two items. These guidelines allow for more cases to be processed by the Crime Lab in a shorter time frame. The policy allows for additional items to be processed if there are extenuating circumstances that are approved by the Crime Lab.

For homicides, serial offenders, critical incidents, or complicated cases, the Crime Lab uses case evaluation meetings that are defined by the Case Evaluation policy. Case evaluation meetings bring together the case and scene agents along with subject matter experts (SMEs) from the different laboratory sections and often the prosecutor. These meetings typically occur a few weeks after the incident to allow for the investigation to go through its initial fact-finding process prior to starting laboratory analysis.

During these meetings, an overview of the case is discussed along with the individuals involved, the evidence collected up to that point in the investigation, and the CODIS eligibility of those items. The discussion results in the identification of the best evidence to process in the first round that all parties agree to. A formal document is also created at the conclusion of the meeting that includes where each item was found, how it is believed to be related to the crime and suspect(s), and that all necessary standards have been collected for the case. This document is retained in the Laboratory Information Management System (LIMS) for future reference and discovery.

This publication is available free of charge from: https://doi.org/10.6028/NIST.IR.8503

Importantly, SMEs who attend the case evaluation meeting are not assigned the case for analysis. The SMEs serve as consultants to contribute to identifying the best evidence that can be tested with the best scientific processes to generate information that may answer the questions in the criminal investigation.

For critical incidents, such as officer-involved shootings, the case evaluation is done on scene so evidence can be processed in a timely manner, and reports released to maintain department guidelines for transparency. The detective for the Crime Lab and the civilian investigators respond to the scene of the officer-involved shootings to assist with crime scene response, evidence transfer if necessary, and scene processing.

After evidence is submitted to the Crime Lab using the Evidence Acceptance policy and Case Evaluation policy, notes are documented on the laboratory requests by the case management personnel for each section for the scientists to use for processing without needing to know additional information about the case. As the laboratory requests are received in LIMS, only the laboratory sections that need the case synopsis are provided with that information. Most sections only provide instructions for processing. To manage this information and the flow of cases, the Crime Lab uses one detective, two civilian investigators, and one representative for each section. The person assigned to oversee case management is typically not assigned to process any of the evidence on the case. For CODIS Administrators and DNA analysts, additional information is provided to ensure CODIS eligibility and that all applicable standards have been submitted.

In extremely time-sensitive investigations, the Crime Lab also has a Scientific Response Team (SRT) policy to bring evidence into the laboratory for analysis as quickly as possible. This policy allows for some normal procedures to be bypassed, such as formally impounding items prior to being taken to the Crime Lab. Laboratory requests can also be generated in LIMS versus the department's record management system to expedite the analysis.

The comprehensive approach to evidence processing and case management used by the Phoenix Crime Lab ensures that investigative information is provided as efficiently and effectively as possible to resolve cases and get them ready for trial using the highest standards and quality.

10.5.4 Transparency

Transparency is another measure used to support FSSP autonomy and independence. This includes training and providing criminal justice partners with access to documents, reports, and resources to ensure they can obtain the information they need. This can be achieved by publishing policies, procedures, quality system documents, and corrective actions in a web-based environment. This access is becoming more and more common with FSSPs publishing these records on their outward-facing websites.[779]

10.6 Shaping FSSP Culture

Culture is integral to an FSSP's success in producing reliable, high-quality results and to FSSP personnel's overall satisfaction and well-being. FSSP leadership will significantly impact FSSP

[779] Houston Forensic Science Center. Record Search. Accessed March 27, 2024. https://records.hfscdiscovery.org/.

culture, whether through conscious or unconscious influence. **Figure 10.2** summarizes several competencies encompassing strong leadership.[780]

Figure 10.2: Competencies needed by FSSP leadership personnel.

Figure originally appeared in Martina Bison-Huckaby's presentation the EWG and adapted with permission.[781]

Organizational culture will reflect the values and practices of its members. FSSP leadership must determine the current cultural environment and whether it aligns with the vision and mission of the organization. Leadership is responsible for ensuring that the entire organization understands the direction of cultural growth and the plan to get there.

Organizational culture can influence a wide range of employee behaviors, including employee turnover, commitment to the organization, job satisfaction, ethical behavior, and employee engagement. FSSP leadership personnel must be cognizant of the FSSP's culture and take an active role in guiding it. A strong organizational culture emerges when FSSP leadership and analysts develop unified behavior, values, and beliefs.[782] Although leadership is a driving force behind organizational culture, the culture itself influences every level of employee work. Cultures built around ethics and quality of work will serve as a model for employees' behavior and attitude toward performing casework analysis. Cultures of teamwork and innovation will help keep

[780] Information presented by Martina Bison-Huckaby to the Expert Working Group during a virtual meeting on 11/30/2020 – Presentation titled *Focus on Forensic Management Competencies Crucial for Successful Leadership.*

[781] Ibid.

[782] Tsai Y. Relationship between Organizational Culture, Leadership Behavior and Job Satisfaction. *BMC Health Services Research*. 2011; 11:98. doi:10.1186/1472-6963-11-98.

employees engaged in the future of the FSSP and provide a sense of ownership in the direction of FSSP growth.

FSSPs can guide their corporate culture by following these guidelines, proposed by Groysberg et al.:[783]

- "Articulate the aspiration."[784] What is the organization's purpose? Why does it exist?[785]
- "Select and develop leaders who align with the target culture." [786] Ensure that senior management understands the culture that the organization is striving for and has individual leadership styles that support growth.
- "Use organizational conversations about culture to underscore the importance of change." [787] Keep employees informed about the priorities and vision of the FSSP so they can enact changes and provide feedback to leadership.
- "Reinforce the desired change through organizational design."[788] Adjust workflows and processes to conform to the desired organizational culture and strategy. Modify organizational structures to reinforce the desired culture.

10.6.1 Morale

Employee morale has a critical influence on an organization's culture and functionality. In FSSPs, most of which are part of a larger law enforcement organization, political behavior (or the perception of political behavior) can significantly impact employee job satisfaction. Political behavior includes hiring or promoting based on nepotism and making policy decisions to appease collaborators/customers contrary to best practice guidance.[789] Non-managerial employees tend to be more sensitive to political behavior because they have less control over their work environment.

In a highly political work environment, FSSP employees may not perceive their efforts and contributions as being appropriately recognized and rewarded, which may decrease satisfaction with colleagues, supervisors, the organization, and the job itself.[790] FSSP leadership can employ several strategies to counteract the perception of workplace politics. Establishing a clear strategic vision allows employees to feel more involved in workplace decisions, as does ensuring that each

[783] Groysberg B, Lee J, Price J, Yo-Jud Cheng J. The Leader's Guide to Corporate Culture. *Harvard Business Review*. 2018. https://hbr.org/2018/01/the-leaders-guide-to-corporate-culture

[784] Ibid.

[785] Sinek S. *Start with Why: How Great Leaders Inspire Everyone to Take Action*. Portfolio: New York, NY, 2009. doi:10.1037/e515802011-001.

[786] Groysberg B, Lee J, Price J, Yo-Jud Cheng J. The Leader's Guide to Corporate Culture. *Harvard Business Review*. 2018. https://hbr.org/2018/01/the-leaders-guide-to-corporate-culture

[787] Ibid.

[788] Ibid.

[789] Dawley DD, Munyon TP. The Effects of Politics on Job Satisfaction in Crime Lab Employees. *Forensic Science Policy & Management: An International Journal*. 2012; 3(4):159-64. doi:10.1080/19409044.2013.826306.

[790] Ibid.

employee understands the significance of their responsibilities and role within the organization. Offering opportunities to be involved in the growth of the FSSP—whether by participating in strategic planning, taking part in research or validation studies, or participating in training sessions—can help FSSP personnel feel invested in the future of the FSSP.[791]

Increasing analysts' job autonomy and efficiency also helps increase their overall job satisfaction.[792] One way that FSSPs can increase job autonomy is by affording analysts' independence in the testing process, within the confines of the established quality system. This autonomy could be a function of role or work experience, so that a senior analyst may have more autonomy than an analyst who has just completed training. For example, an analyst could be allowed to choose when they would prefer to write reports versus work in the laboratory. Allowing DNA analysts to have more freedom in the decisions made during their daily tasks can improve their overall job satisfaction.[793]

A component of employee morale is the degree to which employees support each other on a peer-to-peer level. FSSP leadership can support morale by allowing personnel to participate in optional opportunities to bond outside of casework. This bonding could be through on-site activities, such as holiday celebrations or team-building activities, or off-site activities, like volunteer events or dinner outings. Some of the most effective activities allow employees to verbalize and celebrate how they appreciate their colleagues. FSSP leadership should try to learn about employees personally, so employees feel valued as individuals and not just a function of case completion.

FSSPs experience a constant need for change in response to external and internal pressures. External pressures can include changes as developers create and improve new technologies, changes made by accrediting bodies to standards documents, or legislative modifications that impact workload or testing timeframes. Some internal pressures can serve to improve forensic practice, such as adapting workflow to increase efficiency or improve quality of work or implementing LIMS to increase transparency and improve documentation.

Other pressures may not serve to improve practice, including case-specific pressures like high-profile cases where FSSPs have failed to take appropriate bias-reducing steps or where those steps have nonetheless failed to prevent inappropriate pressures from reaching the analyst. How FSSP leadership approaches these changes will impact FSSP personnel's acceptance of the

[791] Ibid.

[792] Ibid.

[793] Holt TJ, Blevins KR, Foran DR, Smith RW. *Examination of the Conditions Affecting Forensic Scientists' Workplace Productivity and Occupational Stress - Executive Summary*. 2016. https://www.ojp.gov/pdffiles1/nij/grants/250234.pdf.

changes. Therefore, leaders must recognize that different pressures may require different means to incorporate changes into a workflow.

Becker et al. conducted leadership workshops with FSSP managers and found that managers most frequently use rational persuasion (i.e., using logic and facts to explain why a request is important) to influence their personnel. Other tactics include inspirational appeals (e.g., linking proposed ideas to a person's values), consultations (e.g., asking for suggestions on how to improve practice), and collaboration (e.g., offering to show the person how to do a task).[794] However, not all personnel respond to tactics in the same way. For example, when trying to determine whether a new method for extraction might be advantageous, a consultative approach with section personnel may encourage personnel to share their input and gain buy-in for validation and implementation of a new technique, as opposed to that decision being made by management and presented to section personnel through rational persuasion. Role-play exercises can help FSSP (aspiring) leaders expand their skill sets and try different responses to leadership challenges. A leader trained in multiple influence strategies will be better equipped to respond to varying pressures and keep personnel engaged.

10.6.2 Peer Pressure

A key component within the organizational structure of an FSSP is the impact of social interactions (i.e., peer pressure). Within social interactions, there are a variety of possible outcomes for organizational culture, including complete agreement, where everyone shares the same beliefs; complete disagreement, where everyone holds a different belief; and various meta-states, where there are clusters of agreement to varying degrees.[795]

Ellinas et al. conducted a study that shows the effects of peer pressure on an organization's behavior where individuals are more willing to change their behavior if the people around them are already engaged in that behavior.[796] This study demonstrated that although individuals strive for cognitive consistency, they may forego it for the sake of social conformity.[797] Individuals may act against their personal belief structure to better accord with the rest of the organization because of peer pressure and social rank. For an FSSP with a strong quality culture, this can mean that analysts will conform to quality measures or documentation protocols even if they do not personally understand their importance. Conversely, an FSSP with a lax culture of quality can

[794] Becker WS, Dale WM, Pavur EJ. Forensic Science in Transition: Critical Leadership Challenges. *Forensic Science Policy & Management: An International Journal*. 2010; 1(4):214-23. doi:10.1080/19409044.2010.508507.

[795] Ellinas C, Allan N, Johansson A. Dynamics of Organizational Culture: Individual Beliefs Vs. Social Conformity. *PloS One*. 2017; 12(6):e0180193. doi:10.1371/journal.pone.0180193.

[796] Ibid.

[797] Ibid.

influence conscientious employees to cut corners if they see peers doing so without consequences.

In organizations with a simple structure (e.g., few analysts and one TL), there is likely to be greater peer pressure to adhere to the same protocols. This can lead to analysts adopting those actions as part of their personal belief structure. In more complex organizations, there may be greater drift from the organizational standard as analysts are further removed from senior leadership. In these cases, it is important for each level of management to reinforce the organizational values and encourage those under their supervision to adhere to those values. An FSSP will achieve an optimal risk culture if there is clear guidance on best practices from FSSP leadership and if individuals model those behaviors at every level.

FSSPs often cite quality as a key component of their organizational structure. Srinivasan and Kurey identified two key components of a "true culture of quality": emphasis on quality and peer involvement.[798] Employees are more likely to perceive a culture of quality from an organization's leadership if they hear constant messaging from all levels of management. This messaging must be consistent and credible.[799]

Management must emphasize the importance of quality by including quality measures as a part of their personnel evaluation process. A quality culture also hinges on peers holding one another accountable and routinely raising quality as a topic of team discussion. All employees must understand and take ownership of their role within the quality system.

10.6.3 Risk Culture

Risk culture is the shared attitudes, beliefs, and behaviors of an organization's employees towards risk.[800] It is the way that people in an organization think about, talk about, and manage risk. A strong risk culture is one where employees are aware of the risks that the organization faces, are willing to take calculated risks, and can manage risk effectively. A culture of transparency, accountability, and open communication promotes identification of potential risks before they become problematic.

One of FSSP leadership's primary responsibilities to reduce risk is to ensure that appropriate standard operating procedures (SOPs) are implemented after validation and represent the best practices and best available technologies, to the extent possible (see ***Sec. 8.3*: Scientific Quality**

[798] Srinivasan A, Kurey B. Creating a Culture of Quality. Harvard Business Review. Accessed March 27, 2024. https://hbr.org/2014/04/creating-a-culture-of-quality.

[799] Ibid.

[800] Brooks DW. Chapter 6: Creating a Risk-Aware Culture. *Enterprise Risk Management*. Wiley Online Library: 2009:87-95. doi:10.1002/9781118267080.ch6; Grieser F, Pedell B. Exploring Risk Culture Controls: To What Extent Can the Development of Organizational Risk Culture Be Controlled and How? *Journal of Accounting & Organizational Change*. 2021; 18(5):752-88. doi:10.1108/jaoc-11-2020-0189.

and Standardization). SOPs that change too frequently can cause confusion and stress among personnel. SOPs should be consistent throughout multi-FSSP systems, soliciting input from all participating FSSPs. For example, the Texas Department of Public Safety created an advisory committee comprising the TLs from each FSSP in the system, with a rotating chair. Working in collaboration, the board decides how to validate and implement new techniques and technologies.[801]

One way to encourage a culture of open communication and risk mitigation is to allow analysts to have input on the strategic vision of the FSSP. This can promote personnel buy-in on new projects, such as deciding which technologies or techniques to prioritize for validation. By giving analysts a voice in how the FSSP is run, they are more likely to feel invested in its success and take ownership of their work. This can lead to increased productivity, improved quality, and reduced errors. In addition to allowing analysts to have input on the strategic vision of the laboratory, FSSP leaders should also encourage feedback on both positive and negative elements of SOPs and other FSSP operations. This feedback can be used to identify areas where the FSSP can improve and to make sure that the FSSP is operating in a safe and efficient manner.[802]

10.6.4 Non-Punitive Error Culture

In developing FSSP culture, leadership has the critical responsibility to ensure they handle errors appropriately and only use punitive measures when necessary. A non-punitive error culture is a work environment where mistakes are not punished. Instead, they are seen as opportunities to learn and improve.[803] FSSPs can most effectively manage errors when focusing on the system itself, not the individual (see ***Sec. 2.5: Error***).[804] If FSSP personnel are afraid of being punished for making mistakes, they are less likely to report them. Failure to report errors can lead to downstream issues, as undetected mistakes may not be identified and remedied in time to prevent a deleterious event.

[801] Information presented by Brady Mills to the Expert Working Group during a virtual meeting on 01/11/2021. Presentation titled: *Validation: Texas DPS Crime Laboratory Perspective.*

[802] Dawley DD, Munyon TP. The Effects of Politics on Job Satisfaction in Crime Lab Employees. *Forensic Science Policy & Management: An International Journal*. 2012; 3(4):159-64. doi:10.1080/19409044.2013.826306.

[803] Keith N, Frese M. Enhancing Firm Performance and Innovativeness through Error Management Culture. In: Ashkanasy NM, Wilderom CPM, Peterson MF, eds. *The Handbook of Organizational Culture and Climate*. 2nd ed. SAGE Publications, Inc: Thousand Oaks, CA, 2011. doi:10.4135/9781483307961; van Dyck C, Frese M, Baer M, Sonnentag S. Organizational Error Management Culture and Its Impact on Performance: A Two-Study Replication. *Journal of Applied Psychology*. 2005; 90(6):1228-40. doi:10.1037/0021-9010.90.6.1228.

[804] Information presented by Joseph Keebler to the Expert Working Group during a virtual meeting on 01/25/2021. Presentation titled: *Applying Human Factors Science to Forensic Errors*.

10.7 Learning Organization

Organizational learning integrates individual and team-based learning experiences into routines, processes, and structures to enhance performance.[805] A learning organization prioritizes learning across all activities.[806] While FSSPs heavily rely on accreditation and FBI QAS for quality assurance, this falls short of fostering comprehensive organizational learning. To become a learning organization, FSSPs must actively engage in shared quality vision, leadership empowerment, knowledge sharing, innovation, and problem-solving.[807] By adopting a systems approach to learning, FSSPs can become agile and responsive to dynamic environments, making quality a core value rather than a mere obligation.[808]

Learning organizations require leaders committed to fostering a culture of continuous improvement. FSSP leadership plays a crucial role in identifying performance gaps and opportunities for development.[809] Effective leaders communicate a vision of continuous improvement and learning throughout the organization, emphasizing the value of embracing *failure* as part of the learning process. This is counter to a traditional or legacy approach to a quality system in FSSPs with a punitive quality culture. Failures *will* occur, and it is the ability of the individual, team, and organization to learn from these failures in a positive and constructive manner that contributes to a progressive and iterative growth in quality (see ***Sec. 10.6.4*: *Non-Punitive Error Culture***).

A shared vision enables the FSSP personnel to be proactive in their efforts toward continuous improvement. Leaders initiate and create opportunities that enable employees to understand, contribute, and practice that shared vision, which furthers progress and development. As such, FSSP leaders must formally dedicate resources at all levels of the organization to the learning process, so the organization is continually improving by developing its analysts' knowledge, skills, and abilities (KSAs). This includes time, funding, and opportunities afforded to FSSP personnel, including analysts, technical support, and administrative personnel, to build their capabilities and contribute to organizational growth. This leadership empowerment allows the FSSP to be agile and proactive in adverse and evolving environments.

[805] Schilling J, Kluge A. Barriers to Organizational Learning: An Integration of Theory and Research. *International Journal of Management Reviews*. 2009; 11(3):337-60. doi:10.1111/j.1468-2370.2008.00242.x.

[806] Wick CW, León LS. From Ideas to Action: Creating a Learning Organization. *Human Resource Management*. 1995; 34(2):299-311. doi:10.1002/hrm.3930340207.

[807] Stelmaszczyk M. Relationship between Individual and Organizational Learning: Mediating Role of Team Learning. *Journal of Economics and Management*. 2016; 26:107-27. doi:10.22367/jem.2016.26.06.

[808] Wick CW, León LS. From Ideas to Action: Creating a Learning Organization. *Human Resource Management*. 1995; 34(2):299-311. doi:10.1002/hrm.3930340207.

[809] Ibid.

Information sharing and knowledge transfer are the medium through which learning occurs and are characteristics of a learning organization. Knowledge transfer and information sharing have been positively associated with improved organizational performance and increased learning.[810] Systems, processes, and practices that are incorporated across the organization support knowledge transfer and information sharing. This is particularly important when it comes to learning from failure.

FSSPs should have formal systems in place to address nonconformities by understanding the root cause of the event, its impact on related casework, and the adoption of corrective and preventative actions to limit future risk. To maximize the benefit of these processes, the information related to these events should be shared with FSSP personnel in a transparent, respectful, and non-punitive manner.[811] This creates more opportunities for employees to be creative and anticipatory and to solve problems when they arise.[812]

Innovation and problem-solving are central to advancing organization performance. Learning in organizations leads to creativity, innovation, competitive advantage, and overall improved performance.[813] When these practices are incorporated as a normal part of the business process, the learning process and resulting actions create an ongoing cycle of continuous improvement. Quality must also be incorporated into this cycle so that the actions provide value to the organization (see ***Callout Box 8.1*** for Demings Cycle of Plan-Do-Study-Act).[814]

10.7.1 Individual, Team, and Organizational Learning

Learning is a requirement for both short- and long-term organizational improvement. Collective learning processes translate into practices that positively affect organizational performance.[815] Although learning begins at the individual level, there is a joint responsibility for organizations, teams, and individuals to identify, provide, and take advantage of opportunities to enhance KSAs.[816] Advancement of individual-based skill sets corresponds to increases in organizational learning at both the team and organizational levels.[817] A model of organizational learning is presented in **Table 10.3**.

[810] Imran MK, Ilyas M, Fatima T. Achieving Organizational Performance through Knowledge Management Capabilities: Mediating Role of Organizational Learning. *Pakistan Journal of Commerce and Social Sciences*. 2017; 11(1):106-25. doi:10419/188284.

[811] Ibid.

[812] Ibid.

[813] Ibid.

[814] Denzau AT, Minassians HP, Roy RK. Learning to Cooperate: Applying Deming's New Economics and Denzau and North's New Institutional Economics to Improve Interorganizational Systems Thinking. *Kyklos*. 2016; 69(3):471-91. doi:10.1111/kykl.12117.

[815] Schilling J, Kluge A. Barriers to Organizational Learning: An Integration of Theory and Research. *International Journal of Management Reviews*. 2009; 11(3):337-60. doi:10.1111/j.1468-2370.2008.00242.x.

[816] Stelmaszczyk M. Relationship between Individual and Organizational Learning: Mediating Role of Team Learning. *Journal of Economics and Management*. 2016; 26:107-27. doi:10.22367/jem.2016.26.06.

[817] Ibid.

Table 10.3: Model of organizational learning[818]

Level	Organizational Learning Processes	Examples
Individual	Intuiting: The process of developing new knowledge, skills, and abilities on the individual level.	• Analyst training and competency • Review of current DNA research literature • Participation in conferences, workshops, and courses
Team	Interpreting: Sharing knowledge between individuals and teams.	• Presentations and training for peers and collaborators • Analyst discussion of an interpretation of a complex DNA mixture
	Integrating: A shared understanding is achieved within a group or team that allows for collective action.	• Validation projects • Process improvement projects
Organizational	Institutionalizing: The shared understanding is formally adopted into the routines, practices, and policies of the organization which becomes independent of the individual and team.	• New policies, procedures, routines, and practices are implemented for routine execution (e.g., mixture interpretation protocols, case management systems, Direct-to-DNA approach for SAK testing)

Table originally appeared in Lawrence et al, 2005 and adapted with permission.[819]

It is important for FSSP leaders to support the learning processes at all levels. Although these activities reduce operational resources dedicated to casework, the benefit of a continual commitment to growth has an immeasurable, positive impact on the overall performance of the FSSP. Individual expertise is necessary for FSSPs to perform well and execute their mission and must be advanced continually to remain relevant. Without this expertise, the FSSP's abilities will become stagnant, and the FSSP could be adversely impacted. This includes support for adopting new technologies, improving business processes, and implementing best practice guidance. The knowledge gained becomes institutionalized through a progressive movement from the individual level to the organizational level through the team effort, resulting in better policies, processes, and practices.

Factors that contribute to team learning success include communication between individuals on a team, acquired knowledge that is shared transparently, and the integration of the new knowledge into the organization.[820] FSSP personnel work together as they learn individually with a shared purpose or objective that produces work products that improve the organizational

[818] Lawrence TB, Mauws MK, Dyck B, Kleysen RF. The Politics of Organizational Learning: Integrating Power into the 4I Framework. *Academy of Management Review*. 2005; 30(1):180-91. doi:10.5465/amr.2005.15281451.

[819] Ibid.

[820] Stelmaszczyk M. Relationship between Individual and Organizational Learning: Mediating Role of Team Learning. *Journal of Economics and Management*. 2016; 26:107-27. doi:10.22367/jem.2016.26.06.

condition. From a complex adaptive systems perspective, feedback becomes a critical component of the learning process.[821] Feedback can be used to progress toward the execution of their shared objectives such as a business process improvement project like the Direct-to-DNA approach of testing SAKs or the adoption of probabilistic genotyping. As individual learning supports team learning, team learning in turn supports overall organizational learning.

10.7.2 Barriers to a Learning Organization

Although individual and team learning contribute to organizational learning, there are barriers that limit learning opportunities. These barriers broadly fall into three categories:[822]

1. Actional: Personal – Characterized by individual thinking, attitudes, and behaviors.
2. Structural: Organizational – Characterized by existing routines, structures, and practices including strategy, technology, culture, and policy.
3. Societal: Environmental – Characterized by the external environment, including collaborators/customers, suppliers, technology, and the sociopolitical environment.

Individuals introduce barriers through their thinking, attitudes, and behavior.[823] This can take form in a multitude of ways, including ineffective communication, incompetence, resistance to change, bias, politics, and stress. Organizations may also introduce barriers through organizational strategy, culture, and formal policy.[824] Organizational barriers can take the form of toxic culture, ineffective leadership, unrealistic performance expectations, and outdated organizational objectives. External barriers are those outside the organization, centered on criminal justice partners who either provide an input to the organization or receive an output of the organization. These barriers manifest themselves within organizations as summarized in **Table 10.4**.

[821] Edson MC. A Complex Adaptive Systems View of Resilience in a Project Team. *Systems Research and Behavioral Science*. 2012; 29(5):499-516. doi:10.1002/sres.2153.

[822] Schilling J, Kluge A. Barriers to Organizational Learning: An Integration of Theory and Research. *International Journal of Management Reviews*. 2009; 11(3):337-60. doi:10.1111/j.1468-2370.2008.00242.x.

[823] Ibid.

[824] Ibid.

Table 10.4: Barriers to organizational learning[825]

Category	Organizational Learning Barriers	Examples
Actional – Personal	• Biases and deficiencies in employees • Lack of KSAs • Lack of motivation • Restrictive and controlling management style	• Limited access to learning experiences, knowledge, and practical applications of new knowledge • Management styles critical to supporting a learning climate (e.g., limited access to continuing education opportunities, TL does not share information, limited discussions of quality events preventing learning opportunities, limited opportunities for individual learning) • Fear of taking risks and learning
Structural – Organizational	• Lack of clear, measurable goals and performance feedback • Monolithic corporate culture with homogeneous workforce (i.e., everyone is making the same error) • Strict work rules and regulation • High division of labor • Organizational blame culture	• Everyone is making the same error in the application of the technology (e.g., interpretation errors [mixture studies], inappropriate application of statistics models) • Highly regulated environment which limits ability to learn • Punitive quality culture which penalizes those who make mistakes and limits opportunities to learn
Societal – Environmental	• Complex, dynamic, and competitive market environment • Unclear ideas of success • Cultural distance and low level of experience in relevant culture • Complex, ambiguous, and difficult knowledge • Relevant but implicit and immobile knowledge	• Poor definition of success (e.g., is it quality, quantity, or turnaround times?) • Highly complex knowledge and technology applications resulting in delays in adopting new technologies and poor aggregate understanding of complex concepts (e.g., a new analyst needs to learn all about forensic DNA before establishing competency, whereas an experienced analyst has had a career to learn the same depth of knowledge)

Although these barriers can significantly impede change within organizations, there are strategies to overcome them. The dimensions necessary to be a learning organization, such as a shared vision, leadership empowerment, knowledge sharing, innovation, and problem-solving, form the basis for strategies to overcome these barriers. It is important for leaders, teams, and individuals to have a well-known and understood vision with clear objectives.

Leaders must empower their teams and individuals to be agents of the organization. They must have the authority to create, problem-solve, and innovate. If there is a disincentive to taking risks,

[825] Ibid.

This publication is available free of charge from: https://doi.org/10.6028/NIST.IR.8503

individuals will not seek out opportunities that create learning or growth to move the organization forward. This also requires transferring knowledge and sharing information, which contributes to the organizational memory and become institutionalized, resulting in formal policies, practices, and culture.

Additional strategies that can be used include bringing in outside resources to facilitate change, communication, and process improvement.[826] Pilot programs are another vehicle to help overcome these barriers. Pilot programs allow for new innovations to be tested before widespread adoption. This creates an important feedback loop that contributes to the continuous cycle of improvement. Information gathering, gap analysis, surveys, and other tools can be used to help provide information that both individuals and teams can use in the learning process. There are several strategies that can be implemented, but they must be explicitly pursued, or the barriers summarized in **Table 10.4** will limit organizational learning.

FSSP leaders must provide access to continuing education, continued skill development, and learning resources (see ***Sec. 9.5*: *Continuing Education***). Additionally, the FSSP's quality culture must be focused on continuous improvement through organizational learning that embraces learning from failure. Leadership must practice this in a transparent, open, and supportive manner that reduces the fear associated with risk-taking. Mistakes can be corrected, but misconduct and negligence cannot (see ***Sec. 2.5*: *Error***). Leadership must understand the differences between mistakes, misconduct, and negligence and what they reveal about an FSSP's organizational integrity and credibility. Being a learning organization advances the modern FSSP beyond one that relies solely on accreditation and the FBI QAS.

10.8 Employee Wellness

Employee wellness is one of many cornerstones of any functionally successful workplace. This sentiment is especially true in the forensic science sector, which faces unique challenges related to secondary traumatic stress, vicarious trauma, occupational stress, high throughput nature, and backlog pressures of DNA analysis work. It is the parent organization's and FSSP leadership's responsibility to develop a safe working environment that promotes mental and physical health and fosters open communication about well-being between all employees, regardless of job title.

Management is crucial in forming the foundational basis of a healthy work environment by providing access to various support services, resources, and supporting a healthy work–life balance. However, it is everyone's responsibility to take ownership of their own well-being by using wellness offerings.

[826] McKenna PJ. Strategies for Overcoming Obstacles to Change. *Of Counsel*. 2017; 36(7):6-12. doi:proquest.com/trade-journals/strategies-overcoming-obstacles-change/docview/1915769056/se-2.

This publication is available free of charge from: https://doi.org/10.6028/NIST.IR.8503

The importance of employee wellness can be introduced well before actual employment in an FSSP. Academic programs (e.g., Bachelor of Science and Master of Science degrees in forensic science) should discuss the physical and emotional toll that employment at a forensic agency may inflict on their students. This content should cover the different types of forensic workplace stressors, how to manage them, and practical exercises to help students develop regular coping mechanisms. Understanding the importance of overall wellness should be covered in all forensic science-based academic programs to support full awareness of all future professionals entering the field, regardless of the discipline pursued post-graduation.

10.8.1 Trauma and Stressors Prevalent in Forensic Science

Forensic science professionals, both sworn and unsworn, comprise a group that may be highly susceptible to compassion fatigue, secondary traumatic stress, and burnout.[827] Although these may be more prevalent in crime scene technicians who regularly attend crime scenes, individuals working within an FSSP are not immune to these same traumas and stressors. FSSPs that use hybrid positions in which they expect those in specialized roles, such as an analyst, to respond to crime scene callouts are of special consideration due to multiplied exposure to traumas and stressors while responding to a scene and processing physical evidence collected at the scene in the laboratory.

Hybrid positions may vary between agencies and are often a result of a jurisdiction's crime rate being higher than the unit's response capacity or because of understaffed crime scene units. These factors may contribute to high turnover, resulting in a lack of experienced technicians signed off to handle high-priority crimes (e.g., homicides). In some agencies, specialists may only attend a crime scene in the event of a unique circumstance that requires special processing instructions from the relevant specialist, such as an analyst or latent fingerprint examiner. Despite the typical work environment (e.g., laboratory, crime scene, hybrid) or discipline, all forensic science professionals can be exposed to, and negatively impacted by, stress and trauma which manifests in varying ways.[828]

Understanding the reason for the commonality of stress in the forensic science community is multifaceted. Most obviously, the very nature of forensic scientists' work is sensitive and, in many instances, pushes barriers regarding what a typical layperson would see in their lifetime. Homicides, suicides, sexual assaults, and child abuse or exploitation are just some of the case

[827] Levin AP, Putney H, Crimmins D, McGrath JG. Secondary Traumatic Stress, Burnout, Compassion Satisfaction, and Perceived Organizational Trauma Readiness in Forensic Science Professionals. *Journal of Forensic Sciences*. 2021; 66(5):1758-69. doi:10.1111/1556-4029.14747; Schiro S, Elwood LS, Streed T, Kivisto AJ. Occupational Exposure to Traumatic Evidence and Posttraumatic Stress Symptoms in Forensic Science Professional: Prevalence and Patterns. *Journal of Forensic Sciences*. 2023; 68(4):1259-67. doi:10.1111/1556-4029.15292.

[828] Schiro S, Elwood LS, Streed T, Kivisto AJ. Occupational Exposure to Traumatic Evidence and Posttraumatic Stress Symptoms in Forensic Science Professional: Prevalence and Patterns. *Journal of Forensic Sciences*. 2023; 68(4):1259-67. doi:10.1111/1556-4029.15292.

types that are likely to negatively impact forensic scientists' well-being. Accompanying this, analysts may have unique experiences and histories that exposure to traumatic events or emotional content could exacerbate.[829]

Alongside exposure to emotional and sensitive material (both tangible and intangible), high stress levels in forensic science practitioners can also be attributed to their working environment. Routine exposure to potentially hazardous materials, profuse caseloads, error-free work expectations, lack of tolerance for mistakes, and routinely appearing as an expert witness in court can also cause workplace stress to accumulate.[830]

In addition to employee work requirements and performance expectations, operational and FSSP-based considerations such as lack of funding or staffing leading to overworked employees; poor personnel management; overwhelming, unmanageable, or unsustainable backlogs; and pressure from oversight or partnered criminal justice agencies, other criminal justice partners, including prosecutors and the judiciary, and the media can also manifest high stress levels in forensic science professionals.[831]

Triggers for stress or trauma can be onset by a single case or through the cumulation of many cases caused by large caseloads and high throughput expectations. These job-related considerations may lead to chronic stress and adverse health behaviors such as depression, substance abuse, suicide, various cancers, and premature death.[832] In a research study conducted by Almazrouei et al., 150 forensic practitioners (including 42 DNA analysts) were sampled and asked to participate in a survey regarding workplace stress.[833] The results of this survey indicate that one in three practitioners (36%) often experience stress in the workplace as a result of management or supervisors or evidence backlogs, with DNA analysts being more likely than analysts in other forensic disciplines to attribute high stress to overwhelming evidence backlogs.[834]

Keel linked work-induced psychological stress to employee burnout.[835] The cause of burnout is attributed mainly to job structure, lack of workplace support, and completion of repetitive tasks.

[829] Wild J, McKinnon A, Wilkins A, Browne H. Post-Traumatic Stress Disorder and Major Depression among Frontline Healthcare Staff Working During the COVID-19 Pandemic. *British Journal of Clinical Psychology*. 2022; 61(3):859-66. doi:10.1111/bjc.12340.

[830] Forensic Technology Center of Excellence (FTCoE). ASCLD Emerging Issues: Employee Wellness – Stress, Vicarious Trauma, and Resiliency for Forensic Science Professionals. Accessed March 27, 2024. https://forensiccoe.org/stress-vicarious-trauma-and-resiliency/.

[831] The American Society of Crime Laboratory Directors (ASCLD). *Trauma and Stress in the Field of Forensic Science*. 2019. https://www.ascld.org/wp-content/uploads/2019/02/Trauma-and-Stress-in-the-Field-of-Forensic-Science.pdf.

[832] Ibid.

[833] Almazrouei MA, Dror IE, Morgan RM. Organizational and Human Factors Affecting Forensic Decision-Making: Workplace Stress and Feedback. *Journal of Forensic Sciences*. 2020; 65(6):1968-77. doi:10.1111/1556-4029.14542.

[834] Ibid.

[835] Keel P. Psychological Stress Caused by Work: Burnout Syndrome. *Soz Praventivmed.* 1993; 38(2):S131-2. Psychische Belastungen durch die Arbeit: Burnout-Syndrom. doi:10.1007/BF01305364.

Research quantifies burnout by measuring emotional exhaustion, depersonalization, and reduced personal accomplishment in the workplace.[836] These same metrics can translate the research quantification of burnout to practical usage within the field as a tool for management to gauge their employees' level of burnout. Holt et al. found that nearly 60% of 899 forensic science practitioner respondents indicated that their work emotionally drained them.[837] To prevent, recognize, or respond to manifested employee burnout, vicarious trauma, and stress, FSSP leadership should be familiar with their employees' "strengths, weaknesses, knowledge, training, experience, caseload, and work history."[838]

To better understand the effects of trauma and stress within the forensic science community, in 2019, ASCLD formed a Trauma & Stress Working Group (TSWG). The TSWG aims to increase knowledge, research, awareness, training, and effective preventative and reactive treatment options about stress and vicarious trauma, specifically in forensic science.[839] The TSWG is dedicated to improving practitioner resilience and the forensic science workforce. In addition, the United States Department of Justice, Office of Justice Programs, Office for Victims of Crime has developed a Vicarious Trauma Toolkit, which offers resources and helpful tools to allied criminal justice professional fields, including analysts.[840] This toolkit also details a blueprint plan that agencies can build on to ensure their workplace is vicarious trauma-informed and equipped to form and execute an action plan that will benefit their organization, considering their needs, available resources, and priorities.[841]

10.8.2 Employee Wellness Support Resources

Management should focus on providing proactive support for employees' mental and physical health needs at both the FSSP-wide and FSSP-department levels. This support begins at the enterprise planning level of an FSSP's organizational structure. Many FSSPs offer inclusive and robust benefits packages for employee well-being, retirement planning, and support services; however, these offerings are often FSSP-specific. As a result, there is variation between FSSPs because of organization structure, autonomy status, and jurisdictional locality.

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[836] Slack DP. Trauma and Coping Mechanisms Exhibited by Forensic Science Practitioners: A Literature Review. *Forensic Science International: Synergy*. 2020; 2:310-6. doi:10.1016/j.fsisyn.2020.10.001.

[837] Holt TJ, Blevins KR, Foran DR, Smith RW. *Examination of the Conditions Affecting Forensic Scientists' Workplace Productivity and Occupational Stress - Executive Summary*. 2016. https://www.ojp.gov/pdffiles1/nij/grants/250234.pdf.

[838] Member Resource Committee Stress/Trauma Working Group. *Management Detection and Mitigation of Stress, Vicarious Trauma, and Burnout in Forensic Practitioners*. 2020. https://www.ascld.org/wp-content/uploads/2020/04/Management-Detection-and-Mitigation-of-Stress-Vicarious-Trauma-and-Burnout-in-Forensic-Practitioners-February-2020.pdf.

[839] The American Society of Crime Laboratory Directors (ASCLD). *Trauma and Stress in the Field of Forensic Science*. 2019. https://www.ascld.org/wp-content/uploads/2019/02/Trauma-and-Stress-in-the-Field-of-Forensic-Science.pdf.

[840] Office for Victims of Crime. The Vicarious Trauma Toolkit: Blueprint for a Vicarious Trauma-Informed Organization Accessed March 27, 2024. https://ovc.ojp.gov/program/vtt/introduction.

[841] Ibid.

Parent organization and FSSP leadership should ensure that each employee is aware of their offered benefits, understands the process of enrolling in these benefits, is kept up to date when benefits are replaced or changed in any capacity, and is informed of the correct point of contact for varying services if questions or concerns arise during the employee's tenure. While management offers these benefits, it is ultimately the employee's responsibility to take advantage of them.

Access to an Employee Assistance Program (EAP) is a common subset of an employer's benefits program, which employees may use at any time during their tenure at a workplace. In some instances, EAP services may also be available to the employee after resigning or retiring from the workplace that provided the service. EAPs are typically provided at no cost to the employee and may include passive service options such as initial assessments, short-term counseling options, referral to long-term therapy or psychiatric programs, and follow-up services and resources based on the initial assessment.

An EAP request can be initiated by an employee when the individual wishes to seek assistance with personal or work-related circumstances that have or may impact their mental health, work performance, or overall well-being in any capacity. These services are entirely voluntary and do not require intervention from a third party (e.g., FSSP leadership, human resources representative).

FSSP leadership should ensure they promote EAP services during the employee's onboarding process, including making all relevant EAP contact information readily available to the employee to maintain confidentiality in the process. The non-mandatory, fully confidential nature of EAP services allows employees to seek the help they need without alerting uninvolved individuals or parties, which could make the employee uncomfortable and unwilling to seek assistance when needed. These activities should be supported in an "on-duty" capacity.

In addition to offerings through employer benefits, workplaces should embrace peer support groups (see **Callout Box 10.2a** and **Callout Box 10.2b**). Research conducted by the Defense Centers of Excellence for Psychological Health and Traumatic Brain Injury showed that individuals who share experiences are often better suited to relate to each other's experiences with compassion. This compassion can help peer communication, in which the individual seeking assistance may be more likely to fully share their thoughts and listen to the peer supporter.[842]

[842] Money N, Moore M, Brown D, Kasper K, Roeder J, Bartone P, Bates M. *Best Practices Identified for Peer Support Programs*. Defense Centers of Excellence for Psychological Health & Traumatic Brain Injury. 2011. https://www.mhanational.org/sites/default/files/Best_Practices_Identified_for_Peer_Support_Programs_Jan_2011.pdf.

Callout Box 10.2a: FSSP Peer Support Group Example

One EWG member's organization has an Employee Assistance Unit (EAU) that employs licensed mental health professionals to provide short-term counseling, management consultation, and mental health crisis intervention. This EAU is available to all employees throughout the organization. This EAU also manages programs for the organization focused on work life, crisis intervention, and wellness and resiliency. Information and support are available to employees through EAP professional counselors and peer volunteers via in-person and online events, digital resources, and referral links. Briefings are available to any employee group and can range from an overview of available services to more specific topic areas such as the following:

- Suicide prevention
- Law enforcement trauma and stress
- Deployment stress and reintegration
- Grief & loss
- Managing personal finances
- Mindfulness and other stress-reduction techniques

Volunteer EAP peers are trained to listen supportively, assess, and refer; they also organize wellness events and peer support groups. One support group option is a parenting group that meets once per month with discussion driven by the group participants. As described by the peer organizer, "a group member will pose a question or scenario from recent experience and ask for advice from the other members." This format allows participants to share what has worked for them or what might help their fellow peers.

When in attendance at the parenting support group, the organization's assigned counselor will offer an expert opinion, often explaining child psychology in the process but usually preferring to wait for the participants to give feedback first. Additionally, the organization's counselor encourages participants to share their successes as a parent to acknowledge the positive and not just the negatives.

Programs such as these provide tools to maintain overall well-being with a goal to help each employee perform at their best in the work environment by helping to develop a greater sense of belonging and self-worth. Additional benefits of peer support groups include reducing feelings of intimidation when communicating with peers, the ability to talk to someone who understands the job first-hand, and the potential to obtain support easier, as one does not need to travel to an off-site location.

Callout Box 10.2b: The City of Phoenix's Wellness Program Model[843]

Health and wellness programs are essential to business and employees in that they build an environment of mental and physical well-being which leads to a productive workplace. In today's world of busy schedules, long and sometimes stressful workdays, sitting for extended periods, and quick and potentially unhealthy meals eaten between meetings, employee wellness in the workplace is more important than ever. Employers that assist and support their employees' mental and physical health experience a happier work environment, reduced absenteeism, less employee mental and physical burnout, fewer healthcare costs, and increased employee retention. Efforts focused on employee health and wellness boost job morale and satisfaction while aiding employees in the performance of their roles, increasing productivity and return on investment.

[843] Authored by Erin Hickson and Shawna Hilliard from the Phoenix Police Department Crime Laboratory.

The City of Phoenix has a robust wellness program for the benefit of its employees: programs that encourage and train employees to get up and move, eat in a healthier way, and spend their money in more fruitful ways. Some of the components of the City of Phoenix's wellness efforts include:

- Scheduled and structured employee wellness events such as prostate cancer screenings, mobile mammogram screenings, meditation classes, wellness challenges, and fitness classes.
- Wellness incentives tied to insurance costs.
- An EAP that provides tools to assist employees in every aspect of their life, and tools for supervisors to support their teams through employee assistance resources. This includes mandatory wellness visits every six months for employees that are exposed to traumatic and highly stressful situations including police officers, communications operators/dispatchers, and crime scene specialists.
- Financial wellness including investing and retirement resources.

The Phoenix Police Department offers additional, specialized support for their employees in the form of an EAU. This EAU aids in anger management, alcohol and drug dependency, behavioral health, child and elder care, critical incidents (on- and off-duty), divorce, family issues, grief and loss for adults and children, injuries (on- and off-duty), military service and war veteran needs, and financial management. The EAU provides additional assistance in the form of counseling, mentorships, chaplain services, referrals, and career mapping. The EAU assists employees in navigating all the resources that the City of Phoenix and Phoenix Police Department have to offer.

The Phoenix Police Department's Laboratory Services Bureau (LSB) strives to ensure the success of their team by supporting and encouraging the pursuit of healthy living. Current components of the LSB's wellness program include:

- Healthy snack program
- Healthy recipe share
- Quiet room
- Lactation rooms
- Critical Incident Stress Management (CISM)/peer support staff

The LSB is also dedicated to team building to create a cohesive team that works together and builds genuine connections. Events that are geared towards team building range from potlucks, National Forensic Science Week celebrations, and holiday and appreciation festivities to fundraising competitions between work groups and team building games. These activities build bridges between the different disciplines and work groups through socialization, shared experiences, and encouraging friendly competition, consequently promoting employee engagement and morale.

The CISM unit, to include peer support staff, is part of the EAU. The CISM unit is dedicated to assisting LSB employees with a myriad of life's difficulties by providing crisis intervention, peer support, and resources for psychological services, ensuring the emotional and psychological well-being of employees.

The LSB's Health and Wellness Committee continues to create new projects and programs to promote health and wellness in various ways. A few of the projects that are planned include:

- Designing comfortable, private spaces for the CISM/peer support unit to meet with employees
- Starting a community garden for LSB staff
- Redesigning meeting and lunchrooms to promote serenity, encourage conversation, and induce creativity

As needs evolve, the City of Phoenix's departments endeavor to create additional resources for their employees. It's a continual task that is essential to a positive, thriving work environment.

The formation of an EAU or a CISM team are two avenues that management should consider when attempting to make well-being assistance more immediate to workers and a more normalized practice in the workplace. These peer support offerings should afford resources to civilian personnel and sworn officers, depending on the FSSP's structural and operational autonomy status. This suggestion is in concordance with Recommendation 21 in the *Law Enforcement Mental Health and Wellness Act: Report to Congress*, which states that support should be made available to non-sworn personnel in the same manner as they are available to sworn personnel.[844] In addition, these resources should prioritize providing empathetic support and active listening to those directly or indirectly involved in, or impacted by, traumatic experiences.

EAUs, most commonly comprising mental health practitioners and expert civilians, primarily provide immediate support to personnel who face any obstacle or stressor interfering with their mental well-being. For law enforcement agencies, these units arrive on the scene (sometimes alongside clergy members) to conduct an on-scene debrief with the investigative team and provide post-scene wellness check follow-ups for all personnel involved in investigating and processing the case.

EAUs also assist employees who are experiencing trauma or stress stemming from outside of the workplace (e.g., divorce, illness, loss of a loved one), which may harm their ability to complete quality work. The development of an EAU can be valuable for providing immediate resources to an employee experiencing exigent circumstances that impact job performance within the workplace. If deemed appropriate by an EAU responder, referral to the agency's EAP for continued assistance may help.

Although EAU services commonly provide support to those directly interacting with the scene or victim(s) involved (e.g., crime scene technicians, responding officers), the impact of trauma stemming from cases is more far-reaching than those who have direct interaction or first-hand exposure to the scene or victim(s). Analysts who process derivative evidence within the laboratory are not immune to the impact of the trauma stemming from the scene or arising from case details. Although the EAU support system may initially be for those with first-hand exposure, FSSP leadership should focus on making it available to all employees.

CISM is a tiered-phase crisis intervention system developed to provide support for individuals who are vulnerable to trauma or have undergone a traumatic event. CISM comprises various elements, including pre-crisis preparation, community support programs, critical incident stress

[844] Community Oriented Policing Services. *Law Enforcement Mental Health and Wellness Act: Report to Congress*. 2019. https://cops.usdoj.gov/pdf/2019AwardDocs/lemhwa/Report_to_Congress.pdf.

debriefing, defusing, and other types of crisis intervention resources.[845] Each component comprises proactive or reactive measures to mitigate psychological damage resulting from enduring a critical incident.

The Professional and Continuing Education program overseen by the University of Maryland's Department of Emergency Health Services became the first to offer a university-based CISM certification.[846] First responder knowledge regarding psychological crisis intervention can build proactive mental well-being habits and form healthy reactive coping strategies for individuals who may be involved or associated with critical incidents regularly. Therefore, FSSP leadership should encourage employees to seek certification in CISM if an individual is interested in joining the agency's formed CISM team.[847]

The discussion or disclosure of personal mental health may be uncomfortable for some employees to discuss openly based on previous experiences, personal beliefs, practices, or cultural identities. To break down outdated misconceptions and societal concepts that obstruct the open discussion of mental health, FSSP leadership should support access to and opportunities for engaging in activities that support an employee's emotional well-being.[848] Fostering a work environment that supports the overall well-being of an employee is important to normalizing utilization of these resources, ensuring employees have support when needed.

FSSP leadership has many opportunities and practices to foster an inclusive and compassionate working environment. First, FSSP leadership can consider implementing and using routine mental wellness checks for their employees (see **Callout Box 10.3**). By implementing this practice, management can gauge the overall well-being of all their employees and show employees that they are invested in employee wellness. Regular wellness checks should lead to a healthier and more functional workplace and may help to reduce the escalation of mental health concerns.

Second, FSSP leadership should consider sponsoring and promoting peer support groups within their department that meet and hold sessions on a set timeline as seen fit by FSSP personnel. Forming peer support groups will foster open communication within the workplace and allow for individuals to share their stories and connect on a more personal level, which can promote individual belongingness and team-based unity.

[845] GoodTherapy. Critical Incident Stress Management. Accessed March 27, 2024. https://www.goodtherapy.org/learn-about-therapy/types/critical-incident-stress-management.

[846] International Critical Incident Stress Foundation, Inc (ICISF). Certification of Knowledge in Critical Incident Stress Management (CCISM). Accessed March 27, 2024. https://cismcertifications.org/.

[847] Zemlok R. A First Responder Spouse's Guide to Post Critical Incident Support. Accessed March 27, 2024. https://www.cordico.com/2020/08/21/a-first-responder-spouses-guide-to-post-critical-incident-support/.

[848] Holt TJ, Blevins KR, Foran DR, Smith RW. *Examination of the Conditions Affecting Forensic Scientists' Workplace Productivity and Occupational Stress - Executive Summary*. 2016. https://www.ojp.gov/pdffiles1/nij/grants/250234.pdf.

Third, FSSP leadership should consider forming a co-worker mentoring program. Peer mentorship allows both mentor and mentee to learn from each other's experiences and build positive relationships within the workplace. Furthermore, developing a mentorship program allows interested mentors to gain skills and experience in a leadership position.

Callout Box 10.3: Mental Wellness Checks

Employees working for an FSSP operating within a law enforcement agency's organizational structure will likely have access to some level of employer-provided psychological support. This support may be provided by designated mental health professionals (e.g., therapists, psychologists) contracted to provide personnel with such services.[849] Alternatively, an FSSP may have in-house mental health professionals who have received additional training to handle work-related trauma (both direct and vicarious).

Although any mental health professional can obtain this type of additional training, it is not necessarily the focus of a general licensed marriage and family therapist, unless trauma support is within their area of expertise. A mental health professional working with law enforcement personnel, both sworn and civilian, may pursue additional training in tools specific to treating post-traumatic stress disorder (PTSD). In addition, they may attend professional meetings geared towards law enforcement mental health and wellness.

Having one or more in-house mental health professionals assigned to provide tailored support for FSSP personnel, specifically those assigned to DNA or crime scene investigation units, provides access to support beyond what may be possible via external providers. An in-house mental health professional will be familiar with the FSSP's structure and work environment. In addition, an in-house mental health professional may shadow personnel to ascertain what the specific demands of the job entail.

Having this first-hand knowledge reduces the burden of providing additional background information when seeking services. External mental health professionals contracted to provide these support services likely would not have this contextual information.

In-house support may extend beyond an office visit to include the following:

- Checking in regularly with management and personnel
- Attending unit meetings
- Creating outreach opportunities by presenting on relevant topics such as stress management and the importance of self-care

With in-house support, managers can alert psychological support services when analysts are assigned to work particularly violent or traumatic cases. A mental health professional can then contact analysts directly to check in and remind them of the available services. In the absence of an in-person session, a telehealth session may be provided as an alternative.

Routine contact between an in-house mental health professional and FSSP personnel can destigmatize and normalize seeking help. Repeated visits to the FSSP establish familiarity and comfort and may further encourage someone to seek services when needed. It also facilitates open conversations around mental wellness.

[849] Community Oriented Policing Services. *Law Enforcement Mental Health and Wellness Act: Report to Congress*. 2019. https://cops.usdoj.gov/pdf/2019AwardDocs/lemhwa/Report_to_Congress.pdf.

10.8.3 Holistic Approaches to Mental Well-Being

From a holistic viewpoint, regular and consistent physical activity plays a prominent role in general health, overall well-being, and improving quality of life. The American Heart Association showed that participating in some form of physical activity aids in stress management, regulates sleep cycle and sleep quality, and promotes positive moods, attitudes, and outlooks.[850] Some FSSPs may have an on-site or satellite gym accessible to employees, whereas some FSSPs sponsor discounted rates or no-cost memberships for in-person gyms, virtual trainers, fitness courses, or physical health-related mobile phone applications. In addition, some FSSPs allow on-the-job hours to encourage employees to take advantage of these various employer offerings and prioritize their physical health, which directly impacts their quality of work produced.

Meditation or yoga is also beneficial. This practice can directly improve working memory, cognitive function, flexibility, and ability to suppress distracting information.[851] Meditation can include any manifestation of mindfulness practices, simple breathing exercises, and stress-reduction breaks. Stress-reduction breaks may look different between individuals, but some popular practices include adult coloring books and puzzles. These activities provide passive reversion therapy to employees, relieve stress, reduce anxiety, and promote focus and concentration.[852] If possible, FSSPs should have designated multipurpose rooms that offer various outlets to promote mental well-being and stress reduction. FSSP leadership should provide and encourage analysts to adapt the rooms to fit their wellness needs.

FSSP leadership should continually and regularly plan activities related to reducing stress, such as structured visitations from an agency's emotional support animal or partnering with local or agency-tied humane societies to sponsor animal visitations to the workplace. Introducing a therapy animal into the workplace, whether for a temporary or long-term stay, has been associated with many morale and health-boosting benefits. These benefits include increased job satisfaction and lower stress levels leading to increased productivity, an increased level of job and agency commitment, and increased general health, including positive effects on blood pressure.[853] Before executing any activity, FSSP management should assess how comfortable employees are with being around an animal and address and mitigate any potential cross-

[850] American Heart Association. Why Is Physical Activity So Important for Health and Well-Being? Accessed March 23, 2024. https://www.heart.org/en/healthy-living/fitness/fitness-basics/why-is-physical-activity-so-important-for-health-and-wellbeing.

[851] Davis DM, Hayes JA. What Are the Benefits of Mindfulness? A Practice Review of Psychotherapy-Related Research. *Psychotherapy*. 2011; 48(2):198-208. doi:10.1037/a0022062.

[852] Brown B. Reversion Therapy: Adult Coloring Books and Mental Health. Accessed March 26, 2024. https://www.gearhungry.com/adult-coloring-books-mental-health/.

[853] Spring Arbor University. Do Pets in the Workplace Improve Morale? Accessed March 27, 2024. https://online.arbor.edu/news/do-pets-workplace-improve-morale#:~:text=1%20Happier%2C%20more%20productive%20workers.%20Both%20pet%20owners,if%20they%20could%20bring%20their%20pet%20to%20work.

contamination effects bringing an animal may have within a forensic science workspace or laboratory.

Of equal importance, FSSP leadership should plan activities that promote employee wellness, foster team-based unity among co-workers, and create a sense of belonging for each employee. These events should boost morale and motivation and can be coupled with various wellness elements. These activities could include periodic employee appreciation events that celebrate the work completed by the department and the successes or milestones of those employed within the department.

Optional team-building activities such as cross-sectional luncheons and holiday celebrations can also support the development of positive relationships, not only within the DNA laboratory but also among all forensic discipline sections within an FSSP. Event offerings can promote physical wellness and healthy habits such as regular exercise and clean eating. Planned events can also include ongoing education opportunities such as book clubs or presentations led by co-workers on emerging research about DNA analysis, employee wellness such as building resiliency within the FSSP, or any other relevant topic related to the workplace.

Recommendation 10.5: Forensic science service provider management and parent organizations should support, facilitate, and provide ongoing opportunities for their personnel to improve mental health and wellness, including addressing vicarious trauma, stress, and burnout. Management should:

- **Understand how these issues harm forensic science service provider personnel.**
- **Understand their and the organization's role in contributing to and mitigating workplace stress and burnout.**
- **Encourage DNA analysts to engage in employee wellness opportunities.**

10.8.4 Establishing Effective Work–Life Balance

As a result of the COVID-19 pandemic, remote work has significantly increased and become more commonplace. While some types of work had previously allowed for sole remote work opportunities, the forensic science discipline, which has historically required in-person work, faced the need to adapt to remote or hybrid work environments. Although some forensic science disciplines (e.g., crime scene) never suspended in-person work because of the in-person requirements of the position, some FSSPs allowed for the practice of hybrid work or fully remote positions.

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Although resuming normal services post-COVID-19, some FSSPs are granting autonomy to the employee to determine their capacity and interest in returning to in-person work versus a hybrid or fully remote working position. For individuals who choose to pursue hybrid or fully remote work opportunities, FSSP leadership should ensure that these employees have full access to all necessary resources and software programs, with respect given to FSSP-developed security and privacy considerations. FSSP leadership should also ensure that those who continue to work remotely, either in a full- or part-time capacity, can create designated workplaces in their home, promoting focus and eliminating distractions from personal obligations during set work hours. Employees who choose, or are still required, to work at home should set clear distinctions between regular work hours and off-the-clock hours, as sharing a living space with a workspace can often lead to remote workers feeling as though they live at work rather than work from home.

It is important that FSSP leadership identify the workforce structure that works best for the FSSP and its employees as supported by empirical evidence. Regardless of if this structure takes the form of in-person or remote working arrangements, FSSP leadership should offer a working schedule that supports a harmonious work-life balance for all employees while setting clear expectations. These arrangements can include offering a flexible working schedule (e.g., an alternative to the traditional five-day work week where employees can choose to work more hours on fewer days or design their work schedule as long as they meet a specified number of hours on a predetermined basis), allotting built-in work time for physical exercise and mindfulness practices, developing an equitable policy for overtime pay, and encouraging and promoting the use of paid time off.[854] Affording employees flexibility, independence, and autonomy in their work schedules will aid in building resiliency and autonomy within the workplace.

[854] Holt TJ, Blevins KR, Foran DR, Smith RW. *Examination of the Conditions Affecting Forensic Scientists' Workplace Productivity and Occupational Stress - Executive Summary*. 2016. https://www.ojp.gov/pdffiles1/nij/grants/250234.pdf.

11. Work Environment

11.1 Introduction and Scope

Studies of human factors examine interaction among humans; the hardware and software tools they use; the physical, organizational, and social environments they work in; and their individual characteristics (e.g., sensory and cognitive capabilities and limitations) to better understand performance outcomes such as task efficiency, accuracy, and physical and psychological stress. An understanding of human factors can help forensic science service providers (FSSPs) to design and implement tools, tasks, and environments that increase employee productivity, efficiency, reliability, accuracy, and safety.[855]

As noted in the National Institute of Standards and Technology's (NIST's) *Latent Print Examination and Human Factors Report*[856] and *Forensic Handwriting Examination and Human Factors Report,* [857] physical work environments that do not consider human responses to environmental factors such as noise, lighting, and workstation design can increase stress and reduce task performance. Many human factors elements raised in previous NIST reports also apply to DNA analysts and DNA laboratories.

This chapter complements these previous reports by focusing on human factors considerations related to aspects of the physical environment that can impact analysts in a DNA laboratory, including lighting, noise, air quality, workspace configuration, and task segmentation. This chapter reviews possible interventions and design standards in each of these areas. The recommendations in this chapter and the associated recommendations from the *Latent Print Examination and Human Factors Report* aim to improve both the work environment of DNA analysts and the work products they produce.[858]

11.2 Task-Appropriate Lighting

Despite foundational differences, the terms *illumination* and *luminance* are often used interchangeably. Illumination is defined as the amount of light falling on a surface and is expressed in units of lux (lx) or lumens per square meter (lm/m^2), [859] whereas luminance measures the amount of light emitted (e.g., from a computer monitor) or reflected (e.g., from a

[855] Sanders M, McCormick E. *Human Factors in Engineering and Design*. 7th ed. McGraw-Hill: New York, NY, 1993.

[856] Expert Working Group on Human Factors in Latent Print Analysis. Latent Print Examination and Human Factors: Improving the Practice through a Systems Approach. National Institute of Standards and Technology; 2012. doi:10.6028/NIST.IR.7842

[857] Expert Working Group for Human Factors in Handwriting Examination. Forensic Handwriting Examination and Human Factors: Improving the Practice through a Systems Approach. NIST IR 8282r1. National Institute of Standards and Technology; 2021. doi:10.6028/NIST.IR.8282r1

[858] Expert Working Group on Human Factors in Latent Print Analysis. Latent Print Examination and Human Factors: Improving the Practice through a Systems Approach. National Institute of Standards and Technology; 2012. doi:10.6028/NIST.IR.7842

[859] Sanders M, McCormick E. *Human Factors in Engineering and Design*. 7th ed. McGraw-Hill: New York, NY, 1993.

piece of paper)[860] and is expressed in units of candela per square meter (cd/m^2).[861] DNA analysts perform tasks that rely on color vision, visual acuity, contrast sensitivity, depth perception, and other visual capacities. These visual capacities can vary depending on the quality and amount of lighting available (also called *illumination levels*). With higher illumination levels, observers can make finer evaluative judgments of color, depth, and contrast when accompanied with increased visual acuity, leading to higher-quality visual perception.

Most published illumination recommendations pertain to industrial, recreational, office, and commercial environments.[862] The Expert Working Group (EWG) is unaware of any literature that specifically examines the visual perceptual tasks that DNA analysts perform or any literature that provides recommendations for appropriate illumination levels for these tasks. Even so, the data presented in **Table 11.1** may provide guidance.

Table 11.1 presents recommended illumination level standards for several broadly defined visual tasks for three different age groups. Standards for observers between 25 and 65 years of age are most applicable to the forensic science workforce.[863] For this age group in larger laboratory spaces and for tasks requiring the reading and writing of paper documents and electronic media, illumination levels should range from 300 to 750 lx. For laboratory workbench surfaces where DNA analysts handle and examine evidence samples, illumination levels should be higher—between 500 to 1,000 lx.[864] For comparison, the typical illumination level for a private office is 200 to 500 lx,[865] whereas the illumination level for a supermarket aisle is between 700 to 800 lx.[866] Generally, illumination levels should increase as the visual demands of the task also increase. For instance, the Committee on Recommendations for Quality and Quantity of Illumination of the Illuminating Engineering Society (IES) recommends illumination levels ranging from 3,000 to 10,000 lx for tasks involving the visual evaluation of very fine visual details with low contrast.[867] These illumination levels are comparable to those used in medical operating rooms in the United States.[868] In instances where at least half of the observers are 65 years of age and older, illumination levels should double.[869]

[860] Ibid.

[861] Ibid.

[862] Illuminating Engineering Society. *The Lighting Handbook: Reference and Application*. 10th ed. IES: New York, NY, 2011.

[863] Ibid.

[864] Sanders M, McCormick E. *Human Factors in Engineering and Design*. 7th ed. McGraw-Hill: New York, NY, 1993.

[865] Committee on Recommendations for Quality and Quantity of Illumination of the IES (RQQ). Selection of Illuminance Values for Interior Lighting Design. *Journal of the Illuminating Engineering Society*. 1980; 9(3):188-90. doi:10.1080/00994480.1980.10747897.

[866] Engineering ToolBox. Illuminance – Recommended Light Levels. Accessed March 27, 2024. https://www.engineeringtoolbox.com/light-level-rooms-d_708.html.

[867] Ibid.

[868] Mills E, Borg N. Trends in Recommended Illuminance Levels: An International Comparison. *Journal of the Illuminating Engineering Society*. 2013; 28(1):155-63. doi:10.1080/00994480.1999.10748262.

[869] Illuminating Engineering Society. *The Lighting Handbook: Reference and Application*. 10th ed. IES: New York, NY, 2011.

Table 11.1: Standard recommended illumination levels for different visual tasks based on age group[870]

	Ages of Observers (years)			
	<25	**25–65**	**>65**	
Recommended Illumination Targets (lx)	20	40	80	**Common social activity and large stimuli or high-contrast tasks** Visual task/performance requirements are relatively low. Spaces can be work-related, including gathering spaces and waiting areas.
	25	50	100	
	37.5	75	150	
	50	100	200	
	75	150	300	
	100	200	400	
	150	300	600	**Common relatively small stimuli; more cognitive or fast-performance visual tasks** Visual tasks, including reading or writing high-quality paper documents and electronic media (e.g., computers and tablets) consecutively or simultaneously.
	200	400	800	
	250	500	1,000	
	375	750	1,500	
	500	1,000	2,000	**Visual cognitive tasks involving scrutiny of fine details** Visual tasks requiring close or distant inspection of very small details or low-quality visual images. *Example: Visual inspection for minute traces of body fluid on dark-colored or patterned clothing.*
	750	1,500	3,000	
	1,000	2,000	4,000	
	1,500	3,000	6,000	**Evaluation of unusual, extremely minute details** Visual task/performance is of the highest order. Tasks requiring inspection of faint, low-contrast characteristics or details near the limits of visual acuity. *Example: Examination of slides on an optical microscope or small pieces of evidence under a stereoscope (e.g., a hair root).*
	2,500	5,000	10,000	
	5,000	10,000	20,000	

The choice of illumination level and light location is critical and will vary according to the visual tasks being performed. In rooms where evidence is examined, fixed overhead lighting may be supplemented by adjustable overhead spot or benchtop task lights attached to tabletops that can be removed and reconfigured as needed. In some rooms, fixed lighting may be supplemented by bright sunlight from windows.

The spectrum of sunlight and the light produced by overhead artificial lighting often differ, and overhead lights may emit a slightly bluish or yellowish hue. Differences in the spectrum of light produced by artificial light sources can affect how the color of natural objects or materials such

[870] Ibid.

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as blood may appear to the human eye and therefore can affect detection or identification of a sample. These differences are captured in the color rendering index (CRI) of an artificial light source that is included in its technical specifications. The CRI is a quantitative measure varying between 0 and 100 that expresses the ability of a light source to reveal the color of objects compared with that of a standard light source like sunlight.[871] Lights with higher CRI values render color more accurately and are desirable in color-critical applications[872] such as the evaluation of trace or biological evidence.

The ability to control room illumination level is important for workspaces where alternative light sources are used to examine evidentiary items for trace or biological evidence. An observer's ability to detect the fluorescence of bodily fluids illuminated by alternative light sources may improve at lower illumination levels, depending on the fluid.[873] Dimmable light sources, dedicated rooms, or room-darkening shades allow analysts to adjust the light levels to optimize their visual performance during these tasks.

Inappropriate levels or substandard light placement may cause glare and visual discomfort for the observer. In addition, prolonged use of electronic devices such as desktop and laptop computers, tablets, and mobile phones should be avoided because this can cause digital eye strain.[874] The ocular symptoms of digital eye strain include blurred vision, double vision, fatigue, and redness in the whites of the eyes. Some of the non-ocular symptoms that result from behaviors that occur to compensate for digital eye strain (e.g., sitting or standing with poor posture when trying to improve the perception of digital documents) include neck stiffness, headaches, and backaches.[875] It is increasingly necessary to interact with electronic devices and screens regularly for professional and recreational tasks and activities, so the need for intervention strategies to reduce digital eye strain continues to increase.

Evidence of the effectiveness of designed digital eye strain interventions is mixed, likely reflecting the complex and heterogeneous set of symptoms reported by impacted individuals.[876] Some options to avoid digital eye strain include adjusting lighting levels; adjusting the positioning of screens; customizing screen settings (e.g., contrast, luminance, text size, screen resolution); taking regular breaks from screens; and adding filters to reduce glare or to block blue light

[871] Commission Internationale de l'Eclairage (CIE). *Method of Measuring and Specifying Colour Rendering Properties of Light Sources*. Vol. 13.3. Vienna. 1995. doi: doi.org/10.1002/col.5080200313. https://cie.co.at/publications/method-measuring-and-specifying-colour-rendering-properties-light-sources

[872] Rodriguez RG, Pattini AE. Neonatal Intensive Care Unit Lighting: Update and Recommendations. *Archivos Argentinos de Pediatria*. 2016; 114(4):361-7. doi:10.5546/aap.2016.eng.361.

[873] Ibid.

[874] Coles-Brennan C, Sulley A, Young G. Management of Digital Eye Strain. *Clinical and Experimental Optometry*. 2019; 102(1):18-29. doi:10.1111/cxo.12798.

[875] Ibid.

[876] Ibid.

emitted by screens,[877] though the effectiveness of blue-blocking filters remains controversial.[878] Research also suggests that the symptoms of digital eye strain can be reduced when individuals look at distant objects (i.e., beyond 20 feet) for 20 seconds after every 20 minutes of viewing a digital display, also known as the 20/20/20 strategy.[879]

11.3 Sound and Noise

11.3.1 Noise in Open-Plan Offices

Open-plan offices, which are common in forensic science workplaces, typically consist of cubicles, modular furniture, and hung panels to define work areas for individual employees. The aim of the open-plan office design is to maximize the working floor space while remaining easily adaptable to the needs of the workplace and the individuals using it.[880] Unfortunately, the advantageous architectural properties of open-plan offices may be somewhat counterbalanced by the experiences of those who must share and work in these spaces.

Employees in open-plan offices may complain of insufficient privacy relating to both visual and auditory information. In addition, workers in open-plan workspaces report the distracting effects of irrelevant sound, otherwise known as *noise*.[881] Noise refers to undesired sounds of any quality and is not defined by a characteristic amplitude, frequency, or temporal quality. Rather, what makes the sound a noise is that it occurs at a particular point in time and in such a way that it must be tuned out by, or it impairs the performance of, those completing tasks in its vicinity.[882] Noise can include colleagues' conversations, music, and sounds produced by machinery (e.g., HVACs, computer servers, printers).[883] Field studies have shown that colleagues' speech is one of the most displeasing sources of noise in office workspaces; ringing telephones are another.[884] Sometimes strategies used by others to tune out noise exacerbate the problem for others—the music that one employee plays to aid concentration may be a source of distraction for another

[877] Ibid.

[878] Lawrenson JG, Hull CC, Downie LE. The Effect of Blue-Light Blocking Spectacle Lenses on Visual Performance, Macular Health and the Sleep-Wake Cycle: A Systematic Review of the Literature. *Ophthalmic and Physiological Optics*. 2017; 37(6):644-54. doi:10.1111/opo.12406.

[879] Reddy SC, Low CK, Lim YP, Low LL, Mardina F, Nursaleha MP. Computer Vision Syndrome: A Study of Knowledge and Practices in University Students. *Nepalese Journal of Ophthalmology*. 2013; 5(2):161-8. doi:10.3126/nepjoph.v5i2.8707.

[880] Davis MC, Leach DJ, Clegg CW. The Physical Environment of the Office: Contemporary and Emerging Issues. *International Review of Industrial and Organizational Psychology*. 2011; 26(1):193-255. doi:10.1002/9781119992592.ch6.

[881] Banbury SP, Berry DC. Office Noise and Employee Concentration: Identifying Causes of Disruption and Potential Improvements. *Ergonomics*. 2005; 48(1):25-37. doi:10.1080/00140130412331311390.

[882] Roelofsen P. Performance Loss in Open-Plan Offices Due to Noise by Speech. *Journal of Facilities Management*. 2008; 6(3):202-11. doi:10.1108/14725960810885970.

[883] Holt TJ, Blevins KR, Foran DR, Smith RW. *Examination of the Conditions Affecting Forensic Scientists' Workplace Productivity and Occupational Stress - Executive Summary*. 2016. https://www.ojp.gov/pdffiles1/nij/grants/250234.pdf.

[884] Banbury SP, Berry DC. Office Noise and Employee Concentration: Identifying Causes of Disruption and Potential Improvements. *Ergonomics*. 2005; 48(1):25-37. doi:10.1080/00140130412331311390.

employee. Of course, the effects of noise are not limited to open-plan offices, and there is a need for common courtesy throughout the workplace regardless of office design.

11.3.2 The Impact of Noise on Cognition

Colleagues' unrelated conversations and machine-generated noise have a pervasive effect on those engaged in silent, concentrated work.[885] In addition to distraction and annoyance, employees report lower job satisfaction,[886] increased cognitive workload,[887] and diminished cognitive performance resulting from workplace noise.[888] Noise reduces memory for itemized lists,[889] recall of details from previously read information, and the ability to answer integrative questions requiring evaluation of multiple types and sources of evidence.[890] Employees do not always experience a decline in work productivity because of workplace noise, possibly because some individuals respond to a decline in performance or productivity by expending greater cognitive effort so that their performance is maintained amid noise exposure.[891] As a result, the effects of noise may not be demonstrated or apparent in employees' performance on individual tasks, but may manifest as reports of increased cognitive workload and stress in general when people are working in noisy environments.[892]

The disruptive effect of distracting speech is not predicted by the decibel value of the speech but rather by how intelligible it is.[893] Because the listener's ability to identify individual spoken words is largely unchanged by the intensity range from a whisper to a shout, merely reducing the volume of an overheard conversation will have little impact on annoyance or distraction.[894]

[885] Schlittmeier SJ, Liebl A. The Effects of Intelligible Irrelevant Background Speech in Offices – Cognitive Disturbance, Annoyance, and Solutions. *Facilities*. 2015; 33(1/2):61-75. doi:10.1108/f-05-2013-0036.

[886] Sundstrom E, Town JP, Rice RW, Osborn DP, Brill M. Office Noise, Satisfaction, and Performance. *Environment and Behavior*. 2016; 26(2):195-222. doi:10.1177/001391659402600204.

[887] De Croon EM, Sluiter JK, Kuijer PP, Frings-Dresen MH. The Effect of Office Concepts on Worker Health and Performance: A Systematic Review of the Literature. *Ergonomics*. 2005; 48(2):119-34. doi:10.1080/00140130512331319409.

[888] Banbury SP, Berry DC. Office Noise and Employee Concentration: Identifying Causes of Disruption and Potential Improvements. *Ergonomics*. 2005; 48(1):25-37. doi:10.1080/00140130412331311390.

[889] Wickens CD, Hollands JG, Banbury S, Parasuraman R. Attention in the Auditory Modality. *Engineering Psychology and Human Performance*. 4th ed. Psychology Press: Sussex, England, 2015.

[890] Schneider BA, Daneman M, Pichora-Fuller MK. Listening in Aging Adults: From Discourse Comprehension to Psychoacoustics. *Canadian Journal of Experimental Psychology*. 2002; 56(3):139-52. doi:10.1037/h0087392.

[891] Schlittmeier SJ, Liebl A. The Effects of Intelligible Irrelevant Background Speech in Offices – Cognitive Disturbance, Annoyance, and Solutions. *Facilities*. 2015; 33(1/2):61-75. doi:10.1108/f-05-2013-0036.

[892] De Croon EM, Sluiter JK, Kuijer PP, Frings-Dresen MH. The Effect of Office Concepts on Worker Health and Performance: A Systematic Review of the Literature. *Ergonomics*. 2005; 48(2):119-34. doi:10.1080/00140130512331319409.

[893] Schlittmeier SJ, Liebl A. The Effects of Intelligible Irrelevant Background Speech in Offices – Cognitive Disturbance, Annoyance, and Solutions. *Facilities*. 2015; 33(1/2):61-75. doi:10.1108/f-05-2013-0036.

[894] Haapakangas A, Hongisto V, Eerola M, Kuusisto T. Distraction Distance and Perceived Disturbance by Noise - An Analysis of 21 Open-Plan Offices. *The Journal of the Acoustical Society of America*. 2017; 141(1):127-36. doi:10.1121/1.4973690.

Irrelevant *nonspeech* sounds also interfere with cognitive performance in office, industrial, and educational settings.[895] Sounds with significant acoustic variation in intensity or frequency over time (e.g., beeping tones associated with equipment malfunctions, a printer indicating it is out of paper, or an extraction robot running through its method) are the most disruptive to cognitive processes.[896]

11.3.3 Noise Mitigation Techniques

Noise mitigation methods can reduce the tonal variation of offending sounds or mask the perceptual cues aiding speech intelligibility.[897] Mitigation techniques include adding other sounds such as natural sounds (e.g., recordings of the sound of rain or ocean waves), reverse speech (i.e., recorded speech played backward), and consistent background noise.[898] Other mitigation methods involve using materials that absorb or insulate sounds typical of spoken speech or a combination of any of the methods listed previously. A study conducted by Schlittmeier et al. evaluated two noise mitigation techniques, including reducing the level and intelligibility of distracting speech. They reported that the detrimental effects of distracting speech were only reduced when the mitigation methods were used conjointly.[899] Although performance often improves when masking sounds with white noise and nature sounds, this type of intervention can be unpopular with some listeners because the sound may be perceived as artificial or too monotonous and lacking in temporal fluctuation.[900]

To reduce background speech, some organizations encourage employees to use designated spaces for conversations or meetings with colleagues or collaborators, while others have adopted designated quiet times. Reported benefits of designated quiet times include a greater respect held by individuals of their colleagues' work time, fewer disruptions, and increased productivity. The potential benefits of using noise-canceling headsets are less studied.[901] Noise-canceling headsets are most effective at reducing low frequency (i.e., less than 1000 Hz), sustained sounds

[895] Wickens CD, Hollands JG, Banbury S, Parasuraman R. Attention in the Auditory Modality. *Engineering Psychology and Human Performance*. 4th ed. Psychology Press: Sussex, England, 2015.

[896] Jones D. The Cognitive Psychology of Auditory Distraction: The 1997 BPS Broadbent Lecture. *British Journal of Psychology*. 1999; 90(2):167-87. doi:10.1348/000712699161314.

[897] Schlittmeier SJ, Liebl A. The Effects of Intelligible Irrelevant Background Speech in Offices – Cognitive Disturbance, Annoyance, and Solutions. *Facilities*. 2015; 33(1/2):61-75. doi:10.1108/f-05-2013-0036.

[898] Wickens CD, Hollands JG, Banbury S, Parasuraman R. Attention in the Auditory Modality. *Engineering Psychology and Human Performance*. 4th ed. Psychology Press: Sussex, England, 2015.

[899] Schlittmeier SJ, Liebl A. The Effects of Intelligible Irrelevant Background Speech in Offices – Cognitive Disturbance, Annoyance, and Solutions. *Facilities*. 2015; 33(1/2):61-75. doi:10.1108/f-05-2013-0036.

[900] Haapakangas A, Hongisto V, Eerola M, Kuusisto T. Distraction Distance and Perceived Disturbance by Noise - An Analysis of 21 Open-Plan Offices. *The Journal of the Acoustical Society of America*. 2017; 141(1):127-36. doi:10.1121/1.4973690.

[901] Müller BJ, Liebl A, Martin N. Influence of Active-Noise-Cancelling Headphones on Cognitive Performance and Employee Satisfaction in Open Space Offices. 23rd International Congress on Acoustics, Aachen, Germany 2019. https://pub.dega-akustik.de/ICA2019/data/articles/000062.pdf; Staudenmayer N, Tyre M, Perlow L. Time to Change: Temporal Shifts as Enablers of Organizational Change. *Organization Science*. 2002; 13(5):583-97. doi:10.1287/orsc.13.5.583.7813.

typical of HVAC equipment and motors. Although the use of noise-canceling headsets may interfere with the detection of some sounds, like those indicating equipment malfunctions, safety-critical alarms like fire alarms are designed to exceed background noise by a significant amount and to still be audible.[902] The use of noise-canceling headsets may make some competing sounds or voices more obvious by dulling other sources of noise.[903] An additional consideration if using noise-canceling headphones during some laboratory tasks is the increased potential for contamination if an analyst is touching or adjusting them during an examination.

11.3.4 Distractions and Interruptions

In addition to noise-related distraction, working in open-plan offices exposes employees to increased task interruption by colleagues and other distractors compared with closed-plan offices. These task interruptions are a ubiquitous and challenging aspect of shared workspaces.[904] Their commonality is at odds with their impact on work performance. Findings from the aviation industry demonstrate that task interruptions are one of the main factors contributing to errors made by flight crews performing attention-demanding tasks.[905] Distractions interrupt this workflow and these thought processes, reducing productivity and increasing the risk of error.[906]

Specifically, unsolicited conversations are disruptive to people performing complex cognitive processes that are required to evaluate and interpret information, make decisions, and perform tasks. These kinds of activities and processes are not quick mental tasks—they require prolonged concentration and attention to be completed efficiently and correctly. Exposure to task-irrelevant information about a case via colleagues' conversations has the potential to negate contextual information management procedures (see ***Sec. 3.3.4: Contextual Information Management***) or lead to cognitive bias (see ***Sec. 3.3.3: Cognitive and Contextual Bias and Impacts on Decision Points in DNA Analysis***). Interrupted work processes also take time to be reestablished or reengaged, because the interrupted individual must recall what work they were performing, where they were in their workflow, and what information they were evaluating at the time of the interruption. In the case of email interruptions, one study conducted by Jackson et al. suggested that it takes an average of 64 seconds for an employee to "return to their work

[902] Patterson RD. Auditory Warning Sounds in the Work Environment. *Philosophical Transactions of the Royal Society of London Series B: Biological Sciences*. 1990; 327(1241):485-92. doi:10.1098/rstb.1990.0091.

[903] Müller BJ, Liebl A, Martin N. Influence of Active-Noise-Cancelling Headphones on Cognitive Performance and Employee Satisfaction in Open Space Offices. 23rd International Congress on Acoustics, Aachen, Germany 2019. https://pub.dega-akustik.de/ICA2019/data/articles/000062.pdf

[904] Khoshbakht M, Rasheed EO, Baird G. Office Distractions and the Productivity of Building Users: The Effect of Workgroup Sizes and Demographic Characteristics. *Buildings*. 2021; 11(2):55. doi:10.3390/buildings11020055.

[905] Dismukes K, Nowinski J. Chapter 16: Prospective Memory, Concurrent Task Management and Pilot Error. *Attention: From Theory to Practice*. Oxford University Press: New York, NY, 2006:225-36.

[906] Ibid.

at the same work rate at which they left it."[907] However, the time needed to resume a task likely depends on the nature of the task that was interrupted and the duration of the interruption.[908]

Interruptions are an unavoidable component of a DNA analyst's role because they must often address case-related queries from lawyers, law enforcement officers, and other collaborators while completing other daily or routine tasks. Having the ability to access temporary private workspaces can help DNA analysts avoid unsolicited conversations when completing work requiring complete focus with no external interruptions, thereby reducing the likelihood of accidental errors. Furthermore, silencing electronic alerts, scheduling focus time, and using "do not disturb" signs can reduce external distractions while giving the worker autonomy to determine when deep, concentrated work is most necessary and to engage in steps conducive to supporting that work.

Depending on job function, work needs, and organizational structure, telework or hybrid work might represent alternatives to designated on-site private workspaces depending on the frequency or nature of distractions found in both locations. However, the selection of work environment should be determined by the employee—where one individual may be more distracted in an office environment, another may be more distracted in a home environment.

Recommendation 11.1: Forensic science service provider management, alongside DNA analysts and support personnel, should explore techniques to mitigate noise levels. These techniques could include the use of temporary quiet workspaces, dedicated collaboration spaces, or designated quiet times.

Recommendation 11.2: Forensic science service provider management should afford DNA analysts and support personnel the opportunity to reserve time and space for task-appropriate functions such as a conference room for case reviews or dedicated calendar times to limit task interruptions in the workplace.

11.4 Air Quality and Temperature

Air quality refers to environmental factors, including average and extreme temperatures, humidity, and air contaminants.[909] Crime scene samples such as controlled substances or

[907] Jackson T, Dawson R, Wilson D. Reducing the Effect of Email Interruptions on Employees. *International Journal of Information Management*. 2003; 23(1):55-65. doi:10.1016/s0268-4012(02)00068-3. p. 59.

[908] Brumby DP, Cox AL, Back J, Gould SJ. Recovering from an Interruption: Investigating Speed-Accuracy Trade-Offs in Task Resumption Behavior. *Journal of Experimental Psychology: Applied*. 2013; 19(2):95-107. doi:10.1037/a0032696.

[909] Spengler JD, Chen QY. Indoor Air Quality Factors in Designing a Healthy Building. *Annual Review of Energy and the Environment*. 2000; 25(1):567-600. doi:10.1146/annurev.energy.25.1.567.

decomposing materials may contaminate the air in forensic laboratories. Air contaminants can result from chemicals used in DNA analysis or from reagents used in preceding development or processing techniques by other forensic discipline laboratories.[910] There is also the risk that DNA samples may be contaminated by material suspended in the distributed air.

Because of their design, open-plan office spaces present challenges for controlling airflow and temperature.[911] Comfortable working temperatures range between 69°F and 78°F at 30% relative humidity in the winter and between 68°F and 75°F in the summer when the relative humidity is at 60%.[912] These conditions also reflect the optimal ranges that analytical instrumentation operates, as instruments can be negatively impacted by temperature fluctuations, particularly in warmer environments. The exact values for ideal working temperatures depend on the task and on the monthly outdoor temperatures and relative humidity reported for the workplace's location.[913]

Employees may report greater discomfort when working in geographical regions that experience more significant temperature differences between outdoor and indoor environments.[914] Clothing comfortable for commuting to work in the summer may be uncomfortable in the case of prolonged and relatively sedentary work in an air-conditioned office or laboratory space. This discomfort may be exacerbated when there are 6 to 12 air changes per hour, depending on the kind of chemicals used within the space, as these air changes may increase heat loss via convection.[915] Employees may be encouraged to have an additional clothing layer on hand that is appropriate to their workspace (e.g., office space, laboratory) at any given time to ensure their comfort.

11.5 Ergonomics

Repetitive motion injuries and head and neck discomfort are often the result of poor ergonomic design of employee workstations. Effective ergonomic interventions are associated with reduced injuries, reduced absenteeism, and increased productivity.[916] Many ergonomic adaptations are inexpensive and involve simply adjusting the seat and work surface heights, repositioning

[910] Expert Working Group on Human Factors in Latent Print Analysis. Latent Print Examination and Human Factors: Improving the Practice through a Systems Approach. National Institute of Standards and Technology; 2012. doi:10.6028/NIST.IR.7842

[911] Holt TJ, Blevins KR, Foran DR, Smith RW. *Examination of the Conditions Affecting Forensic Scientists' Workplace Productivity and Occupational Stress - Executive Summary*. 2016. https://www.ojp.gov/pdffiles1/nij/grants/250234.pdf.

[912] American Society of Heating, Refrigerating and Air-Conditioning Engineers Inc. (ASHRAE), American National Standards Institute. *ANSI/ASHRAE Standard 55-2023—Thermal Environmental Conditions for Human Occupancy*. 2023. https://www.ashrae.org/technical-resources/bookstore/standard-55-thermal-environmental-conditions-for-human-occupancy.

[913] Ibid.

[914] Ibid.

[915] Ibid.

[916] de Looze MP, Vink P, Koningsveld EAP, Kuijt-Evers L, Van Rhijn G. Cost‐Effectiveness of Ergonomic Interventions in Production. *Human Factors and Ergonomics in Manufacturing & Service Industries*. 2010; 20(4):316-23. doi:10.1002/hfm.20223.

armrests, arranging computer monitors to minimize glare, and minimizing the range of head and neck rotation.[917] The adjustability of workstations is an important consideration for shared work environments, allowing individual employees to reconfigure the workstation to meet their needs and comfort. Certified ergonomists can evaluate individual workstations and recommend accommodations to adapt them to the needs of individual employees. If possible, FSSP management should provide ergonomic assessments conducted by a knowledgeable ergonomist for all employees to minimize potential discomfort within the workplace. In addition, some agencies offer free or low-cost ergonomic reviews, which FSSP management should take advantage of.

Office accommodations may include ultrawide monitors, multiple monitors, and standing desks, which have gained popularity within many workspaces over the past decade.[918] The EWG is unaware of any literature specifically examining the potential benefits or drawbacks of ultrawide monitors. As a result, the following discussion focuses on the use of multiple monitors as an accommodation option.

Supplying individuals with multiple monitors enhances multitasking capabilities, thereby improving work productivity.[919] For example, DNA analysts who have dual-monitor setups can open multiple applications or source documents from a Laboratory Information Management System (LIMS) on one monitor while drafting a report on the other. Dual-monitor setups can also allow analysts to compare probabilistic genotyping software (PGS) and electropherogram (EPG) outputs without switching between displays.[920] Users often prefer multiple monitor configurations, and there is evidence that these configurations improve work efficiency.[921] Despite its apparent positive impact on work performance, the use of multiple monitor configurations increases neck rotation, but it is unclear from the published literature whether the reported values are of concern.[922]

[917] Kroemer KHE, Grandjean E. *Fitting The Task to The Human: A Textbook of Occupational Ergonomics*. 5th ed. CRC Press: London, UK, 1997. doi:10.1201/9780367807337.

[918] MacEwen BT, MacDonald DJ, Burr JF. A Systematic Review of Standing and Treadmill Desks in the Workplace. *Preventive Medicine*. 2015; 70(1):50-8. doi:10.1016/j.ypmed.2014.11.011.

[919] Gallagher KM, Cameron L, De Carvalho D, Boule M. Does Using Multiple Computer Monitors for Office Tasks Affect User Experience? A Systematic Review. *Human Factors*. 2021; 63(3):433-49. doi:10.1177/0018720819889533.

[920] Czerwinski M, Robertson G, Meyers B, Smith G, Robbins D, Tan D. Large Display Research Overview. *Extended Abstracts on Human Factors in Computing Systems*. 2006:69-74. doi:10.1145/1125451.1125471.

[921] Colvin J, Tobler N, Anderson JA. Productivity and Multi-Screen Computer Displays. *Rocky Mountain Communication Review*. 2004;2(1). https://workolyk.com/wp-content/uploads/2015/07/utahdisplaystudy.pdf

[922] Stringfellow PF. *Evaluation of Large-Screen Display Use: Identifying Relevant Tasks and Associated Ergonomic Risks*. Doctoral dissertation. Clemson University; 2007. https://www.proquest.com/openview/94064f0f29013091cb9e5663e135702a/1?pq-origsite=gscholar&cbl=18750.

Similarly, standing desks have recently increased in popularity because they reduce the type of sedentary behaviors associated with a range of adverse health outcomes.[923] Standing desks or cost-effective alternatives, such as standing desk converters, encourage workers to alternate between sitting and standing throughout their workday. These desks directly increase non-exercise physical activity, which appears to positively impact productivity and may reduce perceived workload and stress.[924] A review of the literature conducted by Gallagher et al. reports that there is mixed evidence regarding the medical and health benefits of using standing desks.[925]

Well-designed workspaces reflect considerations of the DNA analyst; the tasks they routinely perform; and the physical, physiological, and psychological factors that impact their performance. For example, well-designed spaces consider laboratory workflow in positioning tools and equipment to minimize the amount of walking an employee must undertake while performing work tasks and the number of times an employee is required to interrupt their work to access tools or supplies. These workspaces also include adjustable seating, appropriate lighting, and work surfaces that accommodate the range of employee anthropometric variation and differences in the requirements of other tasks. Ergonomic accommodations should be reevaluated when new office furniture or equipment is purchased or when employees report discomfort or changes caused by medical conditions, aging, or injury.

A workstation designed to fit the population's average height increases the risk of discomfort and injury from prolonged use for those above or below the calculated average, highlighting the importance of adjustable seating and work surfaces to meet the needs of individual workers.[926] These accommodations can reduce the cumulative physical stress caused by repetitive tasks like pipetting or extended periods spent in awkward postures, such as when looking through a microscope. In some cases, employees with physical or sensory disabilities may benefit from accessibility tools (e.g., screen readers, accessibility shortcuts, text-to-speech converters, text magnification, sound amplification) integrated into modern computer operating systems. Poorly designed workspaces can negatively impact employee satisfaction, health, and work productivity, as well as increase errors.[927]

[923] Wilmot EG, Edwardson CL, Achana FA, Davies MJ, Gorely T, Gray LJ, Khunti K, Yates T, Biddle SJ. Sedentary Time in Adults and the Association with Diabetes, Cardiovascular Disease and Death: Systematic Review and Meta-Analysis. *Diabetologia*. 2012; 55(11):2895-905. doi:10.1007/s00125-012-2677-z.

[924] MacEwen BT, MacDonald DJ, Burr JF. A Systematic Review of Standing and Treadmill Desks in the Workplace. *Preventive Medicine*. 2015; 70(1):50-8. doi:10.1016/j.ypmed.2014.11.011.

[925] Gallagher KM, Cameron L, De Carvalho D, Boule M. Does Using Multiple Computer Monitors for Office Tasks Affect User Experience? A Systematic Review. *Human Factors*. 2021; 63(3):433-49. doi:10.1177/0018720819889533.

[926] Kroemer KHE, Grandjean E. *Fitting The Task to The Human: A Textbook of Occupational Ergonomics*. 5th ed. CRC Press: London, UK, 1997. doi:10.1201/9780367807337.

[927] Sanders M, McCormick E. *Human Factors in Engineering and Design*. 7th ed. McGraw-Hill: New York, NY, 1993.

Recommendation 11.3: To optimize user performance and satisfaction, forensic science service provider management and laboratory designers should seek input from DNA analysts to evaluate the usability and accessibility of physical work environment configurations and technologies before they are designed and implemented.

11.6 Segmentation of Tasks

Task segmentation is an "assembly line" type approach to processing samples (also referred to as *division of labor*) and is an effective and efficient mechanism for increasing capacity, decreasing turnaround times,[928] and managing the flow of contextual information (see ***Sec. 3.3.4*: *Contextual Information Management*).** It allows an FSSP to use an analyst's skill sets on a portion of the process and enables analysts to develop specialized expertise in a specific task or collection of tasks. For example, an FSSP may have a grouping of analysts who perform specific portions of the laboratory testing and other analysts who perform data analysis, while other specified analysts perform interpretation of the data and generate reports or perform reviews. Each of these tasks requires specific expertise and knowledge to complete, and analysts can hone their skills by focusing on a specific set of tasks.

Research in other fields has shown that when a worker performs a task repeatedly, the effort to complete subsequent work in the same task decreases while the quality increases.[929] As an alternative to specialization, laboratories may have analysts who are authorized to perform all task segments. This approach helps analysts to be aware of the entire workflow and may prevent single-task fatigue, but it also requires analysts to maintain proficiency in all skills and, depending on the time away from any particular task, may require time to recall the skills needed for tasks performed infrequently.[930] Using a division of labor approach allows samples to be processed through a system in a more efficient manner, allowing an FSSP to increase its capacity.

Segmenting tasks can, however, introduce additional risks, and FSSPs should ensure that the risks associated with such an approach are minimized.[931] Although risk does not equate to decreased quality when properly mitigated, some of the forensic studies focused on measuring efficiency acknowledge that "no measures of quality or accuracy in DNA processing" were included in the

[928] McAndrew WP, Roth MG. Up from "Arts and Crafts": Division of Labor in Forensic Science Laboratories. *Forensic Science Policy & Management: An International Journal*. 2016; 7(3-4):61-8. doi:10.1080/19409044.2016.1153173.

[929] Darr ED, Argote L, Epple D. The Acquisition, Transfer, and Depreciation of Knowledge in Service Organizations: Productivity in Franchises. *Management Science*. 1995; 41(11):1750-62. doi:10.1287/mnsc.41.11.1750.

[930] McAndrew WP, Roth MG. Up from "Arts and Crafts": Division of Labor in Forensic Science Laboratories. *Forensic Science Policy & Management: An International Journal*. 2016; 7(3-4):61-8. doi:10.1080/19409044.2016.1153173.

[931] Tjin-A-Tsoi TBPM. *Trends, Challenges and Strategy in the Forensic Science Sector*. Netherlands Forensic Institute. 2013. https://www.nist.gov/system/files/documents/oles/trends-challenges-and-strategy-in-the-forensic-science-sector-march-2013-_tcm120-494231.pdf.

study.[932] Repetitive, familiar, or uninteresting tasks may decrease engagement with the task.[933] Here, individuals may engage in behaviors to increase cognitive arousal (such as listening to music, audiobooks, or podcasts) that may in turn detract from the task and decrease performance (see also ***Sec. 11.3: Sound and Noise***).

One study on specialization and variety in repetitive tasks concluded that "whereas a specialized assignment strategy is related to improved productivity during the day (i.e., in the short term), variety is related to improved productivity over time (i.e., in the longer term).[934] One way to balance specialization and variety is to create small teams that rotate through a specialized task in addition to their regular duties (e.g., perform screening/DNA analysis most of the time but then have a week of batching duties where they are responsible for running the robotics). This process is likely to be easier in larger FSSPs with more analysts and the ability to space the rotations to balance memory for task with adding variety to the routine.

When samples are passed from analyst to analyst to complete the testing process, it is important that the FSSP maintain continuity in the handling of all samples. The process for labeling sample tubes, and documenting information pertinent to the subsequent testing, must ensure that the next analyst to interact with the samples can complete their tasks appropriately. Systems such as printed tube labels or barcoded tubes can help eliminate issues with label legibility. In addition to ensuring that systems are in place to prevent handling errors, there should be systems that ensure clear communication and coordination of processing strategies to prevent subsequent processing errors.

Using a LIMS to record sample and reagent information and processing instructions can help ensure the necessary processing information for a given sample is consistently recorded, which can help minimize data transfer errors. The utilization of robotic platforms in conjunction with LIMS can help reduce human errors in the movement of samples, record relevant processing notes, and automate data transfer.[935] In addition to minimizing errors, instituting mechanisms such as these also aligns with "lean" principles instituted in many laboratories to eliminate

[932] Hayeslip D, Debus-Sherrill S, Walsh KA. *Evaluation of the Forensic DNA Unit Efficiency Improvement Program*. Washington, DC. 2015. https://www.ojp.gov/pdffiles1/nij/grants/243332.pdf. p. 33.

[933] Staats BR, Gino F. Specialization and Variety in Repetitive Tasks: Evidence from a Japanese Bank. *Management Science*. 2012; 58(6):1141-59. doi:doi.org/10.1287/mnsc.1110.1482; Warr P. *Work, Happiness, and Unhappiness*. Lawrence Erlbaum Associates, Inc.: New Jersey, 2009.

[934] Staats BR, Gino F. Specialization and Variety in Repetitive Tasks: Evidence from a Japanese Bank. *Management Science*. 2012; 58(6):1141-59. doi:doi.org/10.1287/mnsc.1110.1482.p. 1155.

[935] Hayeslip D, Debus-Sherrill S, Walsh KA. *Evaluation of the Forensic DNA Unit Efficiency Improvement Program*. Washington, DC. 2015. https://www.ojp.gov/pdffiles1/nij/grants/243332.pdf.

wasted time during processing as well as avoid communication breakdowns that delay tasks (see ***Chapter 10: Management***).[936]

DNA analysts should be aware of limitations, assumptions, and potential errors in the segments that occur before and after their section of tasks. This awareness allows analysts to be attentive to errors that could happen prior to their work and to be aware of ways to detect and mitigate any perpetuation of an error. Being aware of errors that could occur in subsequent tasks might also help influence the analyst's work or improve their recordkeeping. Analysts should become accustomed to ensuring that all quality checks and controls are in place and reviewed prior to performing their tasks and after completing them (see ***Sec. 8.3.5: Quality Control***). Awareness of all tasks can also improve performance by analysts who are transferring knowledge between tasks and recognizing improvements that can impact multiple tasks.[937]

Of potential concern, task segmentation can lead to a detachment of ownership from the specific case at hand. Although this distance can prevent knowledge of task-irrelevant information, without proper group structure, it can negatively impact quality. Studies in the field of computer programming have shown that when tasks are performed by a team, it is important to have one person who can "act as a single point of contact for others" and "theorize that when such a person exists, the software quality is higher resulting in fewer failures."[938] Although each analyst completes their own specialized task, it can be beneficial to have a single owner who maintains complete awareness of the testing in the full context of the case. Systems should be in place to allow for transparency of the entire process and at least one individual who will review the results and the technical records prior to release.[939] Furthermore, if an analyst "owns" the whole process but only regularly performs a portion of the tasks in it, they should receive periodic refresher training on the whole system to remain proficient in all elements (see ***Sec. 8.8: Proficiency Testing*** and ***Sec. 8.9: Provision of Practice and Feedback Opportunities for Expertise Development***).

[936] Inal TC, Goruroglu Ozturk O, Kibar F, Cetiner S, Matyar S, Daglioglu G, Yaman A. Lean Six Sigma Methodologies Improve Clinical Laboratory Efficiency and Reduce Turnaround Times. *Journal of Clinical Laboratory Analysis*. 2018; 32(1):e22180. doi:10.1002/jcla.22180. Halwachs-Baumann G. Concepts for Lean Laboratory Organization. *Journal of Medical Biochemistry*. 2010; 29(4):330-8. doi:10.2478/v10011-010-0036-5; Kim CS, Spahlinger DA, Kin JM, Coffey RJ, Billi JE. Implementation of Lean Thinking: One Health System's Journey. *The Joint Commission Journal on Quality and Patient Safety*. 2009; 35(8):406-13. doi:10.1016/S1553-7250(09)35057-6.

[937] Staats BR, Gino F. Specialization and Variety in Repetitive Tasks: Evidence from a Japanese Bank. *Management Science*. 2012; 58(6):1141-59. doi:doi.org/10.1287/mnsc.1110.1482.

[938] Bird C, Nagappan N, Murphy B, Gall H, Devanbu P. Don't Touch My Code!: Examining the Effects of Ownership on Software Quality. Presented at: Proceedings of the 19th ACM SIGSOFT Symposium and the 13th European Conference on Foundations of Software Engineering; 2011; Szeged, Hungary. p. 6.

[939] International Organization for Standardization (ISO). *General Requirements for the Competence of Testing and Calibration Laboratories, ISO/IEC 17025:2017*. 2017. https://www.iso.org/standard/66912.html. *See* 7.8.1.1.

Recommendation 11.4: To prevent and detect handling errors when multiple DNA analysts participate in the processing of samples, forensic science service providers should have communication and coordination strategies that require transparency, continual training, and proficiency.

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12. Research Culture and Research Needs

12.1 Introduction and Scope

Research plays a critical role in all aspects of forensic DNA analysis. Academic, industry, and government researchers and research units are typically involved in the early stages of forensic DNA research. These early-stage researchers primarily conduct research that advances the foundational science of forensic DNA analysis and develop and validate cutting-edge and innovative techniques to improve the discipline. In contrast, forensic science service providers (FSSPs) and practitioners generally participate in the later stages of DNA research by validating or verifying new research or technologies for purposes of operational implementation. FSSPs and practitioners also consume and rely on research products to ensure that the procedures they use and the interpretations they provide adhere to best practices and are scientifically sound and empirically supported. Both the production and consumption of research are vital for the ongoing scientific health of forensic DNA analysis. The human factors that strengthen or weaken the quality of these research activities—also known as the *research culture* [940] —are therefore relevant to the EWG.

This chapter describes elements of a positive research culture and, through a systems approach, discusses strategies to strengthen the research culture across all stages of research in forensic DNA analysis. Throughout this chapter, we strive to emphasize the importance for:

- FSSPs to encourage an academic, critical-thinking, "research-minded" approach within their laboratories.
- FSSP management to provide resources and opportunities for practitioners to engage in research endeavors.
- Communication to be strengthened between those producing research (e.g., researchers involved in academia, industry, or government) and those consuming research (e.g., FSSPs, practitioners) to plan strategically to ensure robust evaluations of methods and develop best practices that allow for the appropriate use and application of forensic DNA analysis within FSSPs and in the legal system.
- Federal agencies, academic institutions, and nonprofit organizations to develop and maintain research programs to help advance the field.

[940] Royal Society. Research Culture. Accessed March 27, 2024. https://royalsociety.org/topics-policy/projects/research-culture/.

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12.2 Research Culture

Unlike many forensic science disciplines that have evolved to meet operational policing needs,[941] forensic DNA analysis has evolved from within research institutions and draws on the norms, processes, and knowledge of the basic sciences of biochemistry, molecular biology, statistics, and genetics (among others). Consequently, the research foundations for forensic DNA analysis are arguably among the strongest of all forensic sciences. For example, simple mixture and single-source forensic DNA analysis has been widely regarded as the "gold-standard" forensic science technique.[942] Even so, a research culture extends beyond the scientific and empirical foundations of a discipline to implementation and practice.

A research culture encompasses the behaviors, values, expectations, attitudes, and norms of research communities. A positive research culture in forensic science emphasizes the importance of examining and prioritizing the relationship between research-based knowledge and laboratory practices.[943] Research culture requires a systems approach for understanding who or what influences research, what research has been completed, and how that research has been disseminated. A strong and positive research culture can be instrumental in ensuring that forensic science practices are ethical, accurate, reliable, relevant, and responsive to the needs of end-users and the community.[944]

Typically, discussions about research culture concentrate on the activities of researchers. However, we believe that there is merit in extending the principles and practices connected with favorable research culture to include FSSPs and practitioners as research consumers and contributors. We acknowledge that some components of positive research culture may be more relevant to certain activities during the transition of research into practice (e.g., research and development versus FSSP validation). We also recognize that different readers will approach this report with different needs, interests, and priorities. Therefore, we separately analyze the components of a positive research culture for those primarily *producing* research (e.g., academic, industry, and government researchers) and those primarily *validating, consuming, or contributing* to research (e.g., FSSPs and practitioners).

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[941] Peterson JL, Leggett AS. The Evolution of Forensic Science: Progress Amid the Pitfalls. *Stetson Law Review*. 2006; 36:621-60. ; Saks MJ, Faigman DL. Failed Forensics: How Forensic Science Lost Its Way and How It Might Yet Find It. *Annual Review of Law and Social Science*. 2008; 4(1):149-71. doi:10.1146/annurev.lawsocsci.4.110707.172303.

[942] President's Council of Advisors on Science and Technology (PCAST). *Report to the President: Forensic Science in Criminal Courts: Ensuring Scientific Validity of Feature-Comparison Methods*. 2016. https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/PCAST/pcast_forensic_science_report_final.pdf.

[943] Mnookin JL, Cole SA, Dror IE, Fisher BAJ, Houck M, Inman K, Kaye DH, Koehler J, Langenburg G, Risinger M, Rudin N, Siegel D, Stoney DA. The Need for a Research Culture in the Forensic Sciences. *UCLA Law Review*. 2011; 58(3):725-80.

[944] Australian Academy of Science. Open Science and Scientific Excellence. Accessed May 19, 2023. https://www.science.org.au/curious/policy-features/open-science-and-scientific-excellence.

12.2.1 The Difference Between Validation and Other Research

Before discussing strategies that could positively contribute to the research culture in DNA analysis, it is essential to first distinguish between method validation and broader research efforts. Method validation research is often the most prominent type of research associated with forensic DNA analysis and typically takes two forms. The first is developmental validation. Developmental validation refers to the process of determining the conditions under which newly translated DNA methodologies work well and establishing the limitations of the technology. Developmental validations are primarily completed by researchers.

The second type is internal validation, which in most cases is completed by the FSSP. Internal validations involve demonstrating that established methods and procedures developed by those involved in producing research perform as expected and are robust and reliable when used at individual FSSPs that are considering adopting them (see ***Sec. 8.3: Scientific Quality and Standardization***).

Both developmental and internal validation are essential to providing increased confidence in the reliability, accuracy, and reproducibility of forensic DNA analysis (see ***Sec. 8.3.1: Variation, Reliability, and Validity***). Both forms of validation also require research skills and expertise to be competently executed.

Forensic DNA analysis research extends beyond these forms of method validation to include research endeavors that seek to advance knowledge and understanding in the field. They encompass a wide range of activities, from **foundational research** to **applied research**. Foundational research focuses on expanding the understanding of fundamental concepts and theories, often without immediate practical application. As such, foundational research is largely conducted solely by researchers. Applied research attempts to use scientific knowledge to develop practical solutions to pressing operational challenges. Applied research therefore ideally involves collaboration between those in research roles or institutions and FSSPs.

12.2.2 Research Culture for FSSPs and Practitioners

Beyond the critical role DNA analysts play in internal validation research, it is unclear the extent to which practitioners are supported and encouraged to participate in a forensic DNA research culture either by consuming research products or participating in collaborative research activities. That, in and of itself, is a question that should be resolved to engage in a thorough discussion of the research culture needs of FSSPs. More data are required to fully understand the nature and scope of the opportunities for non-validation-related research engagement available to practitioners. **Callout Box 12.1** describes a subset of key elements of a positive research culture as applied to research activities such as research collaboration and consumption.

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Callout Box 12.1: Key Elements of a Positive Research Culture for FSSPs and Practitioners

- **Integrity**: Participation in research, along with communication of research and its implications by practitioners and FSSPs to third parties (e.g., criminal justice partners), is governed by explicitly stated moral and ethical principles.
- **Openness and transparency**: The research informing best-practice forensic DNA analysis procedures, inferences, and conclusions is readily available to practitioners and FSSPs and is transparently distributed to end-users.
- **Inclusivity**: FSSPs provide analysts with access to research resources (e.g., data, publications, research funding, study leave) and opportunities to participate in research culture, regardless of identity or background.
- **Collaboration and teamwork:** Practitioners and FSSPs work together with researchers and research organizations to efficiently identify and achieve common research goals.
- **Professionalism:** Practitioners and FSSPs are dedicated to using research that is of high quality, reliability, validity, and replicability to improve their professional practice.
- **Continuous learning:** Practitioners and FSSPs are motivated to build their research competence and knowledge as a form of lifelong learning and continuing professional development.
- **Innovation:** Practitioners and FSSPs prioritize contributing to a positive research culture and employing evidence-based best practices for the field.
- **Responsiveness to feedback:** Practitioners and FSSPs are given opportunities to benefit from constructive feedback regarding strengths and areas for improvement in relation to their engagement with research and research culture.
- **Recognition and reward**: Routine participation in, and consumption of, research is valued, and practitioners and FSSPs receive both tangible and intangible benefits from their commitment and contribution to a positive research culture.

There are several systemic factors that can limit the development of a positive research culture for FSSPs and practitioners. Primary factors include accessibility, openness, and transparency. For example, Standard 16.1.2.1 of the Federal Bureau of Investigation's Quality Assurance Standards (FBI QAS) requires that FSSPs "maintain or have physical or electronic access to a collection of current books, reviewed journals, or other literature applicable to DNA analysis";[945] however, the scope and sufficiency of those resources are open to interpretation and vary among FSSPs (see ***Sec. 9.5.3*: *Keeping Up with Critical and Emerging Literature***).

Analysts have access to some publicly available research repositories and curated resources that may supplement what the FSSP can provide (see ***Callout Box 9.1***), but even so, analysts in many FSSPs are not necessarily aware of—or do not have ready access to—the rich research literatures relevant to their discipline and practice. For example, many analysts work within environments where digital access to external research resources is limited or prevented by paywalls.

[945] Federal Bureau of Investigation (FBI). *Quality Assurance Standards for Forensic DNA Testing Laboratories*. 2020. https://le.fbi.gov/file-repository/forensic-qas-070120.pdf/view. Professional Development Standard 16.1.2.1, p. 38.

Consequently, expectations and resources for analysts around the routine participation in and consumption of research are low for some FSSPs.

If analysts and FSSPs do not have access to a diverse array of high-quality, peer-reviewed research publications, and if this access is not valued or facilitated by FSSPs, then it is unreasonable to expect that analysts will routinely participate in, read, reflect on, and integrate research-based knowledge into their practice.[946] However, such engagement is vital to the scientific health and quality of forensic DNA analysis.

The profound implications of FSSPs and practitioners having limited access to research publications, and the associated lowering of research engagement and integration expectations, are exacerbated by a range of other considerations. All qualified analysts in FSSPs accredited to the FBI QAS are required to complete journal review and eight hours of continuing education per year.[947] These same eight hours of potential research engagement can also be used to satisfy the requirements for certification and licensure if analysts choose to obtain those qualifications. Thus, even the most highly credentialed analysts may only be required to read at most a handful of journal articles per year (and may only have read one), even though forensic DNA analysis is a highly complex, technical, and evolving discipline that often plays a central role in the administration of justice.

These modest requirements are not commensurate with the complexity of the field and are not indicative of the positive research culture necessary to assure the scientific health and quality of the forensic DNA discipline. However, there is limited information available to make an alternative evidence-based recommendation. These challenges are also discussed in ***Sec. 9.5****:* ***Continuing Education***. We therefore recommend that researchers and education and training providers invest effort to empirically determine how much research engagement, and in what form, is required for analysts to demonstrate appropriate levels of research-related awareness to ensure the scientific integrity of their procedures, inferences, and opinions.

[946] Chin JM, Ribeiro G, Rairden A. Open Forensic Science. *Journal of Law and the Biosciences*. 2019; 6(1):255-88. doi:10.1093/jlb/lsz009.

[947] Federal Bureau of Investigation (FBI). *Quality Assurance Standards for Forensic DNA Testing Laboratories*. 2020. https://le.fbi.gov/file-repository/forensic-qas-070120.pdf/view.

Recommendation 12.1: To support a positive research culture, forensic science service providers should ensure that DNA analysts have access to, and are supported to engage with, current and emerging scholarship and technologies. This may be achieved by providing opportunities and resources for analysts to be involved in journal clubs, attend scientific presentations or conferences, work collaboratively with academic and industry partners, lead or participate in workgroups or training, or participate in validation or research projects supported by the forensic science service provider.

Beyond regulations and professional credentialing obligations, limited engagement with a positive research culture in forensic DNA analysis, or differences in training backgrounds, can also contribute to inconsistent research engagement. Given the range of educational pathways into the profession, analysts will learn and employ different norms surrounding the role and value of research. For example, analysts joining the profession from forensic science degree programs that primarily focus on the application of science in FSSPs, rather than traditional undergraduate or graduate science degrees, may have less exposure to the benefits and may have little appetite for participating in or consuming research as part of their routine practice. These differences in values and experience can be mitigated to some extent if FSSP management instills consistent values across the organization. However, where those in FSSP management and leadership roles share similar values and a more limited exposure to research value and participation, there is a risk that research engagement will not be adequately prioritized.

Acknowledging the importance of a positive research culture is an essential initial step for FSSPs, but even then, obstacles can still impede the development and maintenance of that culture. FSSPs may struggle to justify expenditure on research-related activities such as attending conferences, subscribing to journals, taking study leave, or dedicating time to research participation. Engagement in research culture requires significant investments of labor, administration, research materials, and access to cutting-edge technology. Embracing a positive research culture demands allocating time and resources to enable FSSP personnel to attend conferences, access and analyze emerging literature, collaborate on research projects, and participate in inter-laboratory studies.

12.2.3 Research Culture for Researchers

Although a positive research culture provides many benefits to those who produce research, there remain several obstacles that researchers must contend with to promote a positive research culture. Some elements of a positive research culture for researchers are described in **Callout Box 12.2**.

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One factor that has the potential to undermine the research culture for researchers is funding availability. Researchers are often required to secure funding from external sources to support their work and even their livelihood. This can be a challenging and time-consuming process with limited prospects of success despite significant time investment. Additionally, funding cycles can be unpredictable and inconsistent, leading researchers to feel uncertain about their employment and financial prospects and limiting their ability to take on long-term projects or explore new areas of inquiry.

Callout Box 12.2: Key Elements of a Positive Research Culture for Researchers

- **Integrity**: Research is governed by explicitly stated moral and ethical principles.[948]
- **Openness and transparency**: Research data and methods are transparently described, freely accessible, and readily reusable.
- **Inclusivity**: Research is conducted in a diverse and inclusive environment with personnel encouraged to value different perspectives and backgrounds.
- **Collaboration and teamwork**: Researchers work together to achieve common goals and share expertise and resources that will advance the field.
- **Professionalism**: Researchers are committed to producing high-quality, reliable, valid, and replicable research.
- **Continuous learning**: Researchers are motivated to develop and are rewarded for the generation of new ideas, fulfilment of lifelong learning, and opportunities for continuing professional development.
- **Innovation**: Researchers are rewarded for creative thinking and exploration.
- **Responsiveness to feedback**: Researchers are provided opportunities to benefit from constructive feedback regarding their strengths and areas for improvement.
- **Recognition and reward**: Researchers receive both tangible and intangible benefits from their commitment and contribution to a positive research culture.

An associated factor also affecting job security and opportunities for advancement among researchers is the pressure to "publish or perish."[949] The need to publish early can often create a culture of competition and stress, which can make it difficult for researchers to explore new and innovative areas of inquiry, pursue high-risk opportunities, or take the time necessary to fully develop their research ideas. This can create perverse incentives that stifle creativity and innovation, leading to a lack of progress in the field. It can also contribute to an environment of secrecy where research ideas, data, and results are neither openly shared nor exposed to sufficient high-quality critical feedback. An additional issue that may undermine research culture is a lack of independence. Although research conducted by interested parties, such as software

[948] National Research Council. *Integrity in Scientific Research: Creating an Environment That Promotes Responsible Conduct*. The National Academies Press: Washington, DC, 2002. doi:10.17226/10430.

[949] van Dalen HP, Henkens K. Intended and Unintended Consequences of a Publish‐or‐Perish Culture: A Worldwide Survey. *Journal of the American Society for Information Science and Technology*. 2012; 63(7):1282-93. doi:10.1002/asi.22636.

developers, may be valuable and add significantly to scientific understanding, we acknowledge the importance—to the legal system and to scientific rigor—of robust independent research conducted by people without direct financial interest in the outcome of the research.[950]

The replication crisis[951]—where the results of many scientific studies are difficult or impossible to reproduce—is one example where a tendency toward secrecy and opaque reporting of methods and analyses has created an environment that inhibited critical evaluation and replication, and has negatively impacted the quality, validity, and accuracy of entire areas of research-based knowledge. This phenomenon was, to some extent, influenced by researchers participating in certain "questionable research practices" [952] that flourish in settings where transparency is lacking, highlighting the crucial role of research integrity in cultivating and maintaining favorable research environments.

Access to appropriate data and research participants is another challenge. Researchers may struggle to find high-quality relevant datasets for their work, which can lead to incomplete or inaccurate results. For example, even basic research broadly examining the role of human factors in expert or high-stress domains will often require involvement from expert practitioners, or access to high-stress workforces and environments. More applied research can require access to realistic casework or operational situations, stimuli, and personnel. One issue regarding access to data that has become a major point of litigation is algorithmic transparency, in particular access to source code of probabilistic genotyping software (PGS) for both researchers and testifying experts. Although full resolution of this complex and difficult issue is beyond the scope of this report, it is noted as an important issue of interest to the legal system and to open science writ large.

Collaboration between researchers, research groups, FSSPs, and practitioners offers one potential solution to these practical research challenges. However, it can be difficult for researchers embedded in research institutions to identify appropriate and willing research partners from outside their field and profession, and to competently navigate the complex array of competing goals and operational restrictions that tend to emerge. As such, many researchers struggle to find and maintain the collaborations with industry and practice that they need to drive their research forward.

[950] President's Council of Advisors on Science and Technology (PCAST). *Report to the President: Forensic Science in Criminal Courts: Ensuring Scientific Validity of Feature-Comparison Methods*. 2016. https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/PCAST/pcast_forensic_science_report_final.pdf.

[951] Ioannidis JPA. Correction: Why Most Published Research Findings Are False. *PLoS Medicine*. 2022; 19(8):e1004085. doi:10.1371/journal.pmed.1004085.

[952] Sacco DF, Bruton SV, Brown M. In Defense of the Questionable: Defining the Basis of Research Scientists' Engagement in Questionable Research Practices. *Journal of Empirical Research on Human Research Ethics*. 2018; 13(1):101-10. doi:10.1177/1556264617743834.

The translation of research into practice can be difficult for many FSSPs.[953] Challenges in validating and implementing noncommercial methods exist, with increased requirements for quality control and training of staff in novel methodologies. Resourcing restrictions within FSSPs may mean that new techniques that assist in only a small number of cases cannot be implemented within the existing resource envelope. Even where a technique may be validated and potentially useful for many cases, translating techniques from research articles into practice takes significant investment and expertise, which FSSPs with high caseloads and backlogs may not be able to sustain.

In summary, academic, industry, and government researchers face challenges including funding pressures, the pressure to "publish or perish," lack of transparency, and difficulty accessing appropriate data and research participants. These obstacles can create a culture of competition and stress, limit job security and opportunities for advancement, stifle creativity and innovation, and negatively impact the quality and accuracy of research-based knowledge. Collaborations between researchers and FSSPs offer one potential solution to practical research challenges, but navigating the complexities of such partnerships can be difficult for those outside operational institutions.[954]

12.3 Opportunities for Expanding and Improving the Research Culture in Forensic DNA Analysis

We have identified four key opportunities for government, academia, industry, and FSSPs to improve research culture across the field of forensic DNA analysis:

1. Embracing Open Science principles to increase transparency and collaboration.
2. Aligning incentives to encourage research engagement across all stages and forms of research.
3. Fostering increased collaboration between academia, industry, and FSSPs to enhance research capacity and effectiveness.
4. Increasing funding for research participation in forensic DNA analysis to support the scientific integrity and quality of the field.

By pursuing these opportunities, the DNA community can create a more robust and effective research culture in forensic DNA analysis that benefits both the field and the wider legal system.

[953] Barcus H, Borchardt A, Dix M, Heurich C, McGrath J, McLeod-Henning D, Ropero-Miller J, Satcher R, Shute R, Witsil A. *Innovation in Forensics: A Community Effort*. Washington, DC. 2020. National Institute of Justice (NIJ). https://forensiccoe.org/private/65481656d71b3

[954] Ibid.

This publication is available free of charge from: https://doi.org/10.6028/NIST.IR.8503

12.3.1 The Case for Open Science

Openness and transparency are key elements of a positive research culture. Open Science is a movement that aims to make scientific research, data, and findings accessible to all.[955] The White House Office of Science and Technology Policy (OSTP) defined *Open Science* as "the principle and practice of making research products and processes available to all, while respecting diverse cultures, maintaining security and privacy, and fostering collaborations, reproducibility, and equity."[956]

Examples of Open Science practices include publicly preregistering research designs and analysis plans prior to starting research (e.g., via Open Science Framework[957]), publishing registered reports where proposed methods are vetted and accepted by journals in principle prior to data collection (e.g., via *Forensic Science International: Synergy*[958]), sharing research datasets and associated metadata, using open-source software (e.g., R[959]), and publishing research findings in Open Access journals or using preprint servers (e.g., bioRxiv[960]) to democratize knowledge. Federal agencies with research and development programs will have to comply with the OSTP public access mandate by 2025.[961] This will require all federally funded, peer-reviewed research publications and the underlying data to be freely accessible upon publication.

Most of these Open Science practices are primarily relevant to the research produced in academic institutions and industry where they can help mitigate biases in analysis and interpretation of results,[962] increase research accountability, facilitate the publication of null findings,[963] promote independent secondary analysis and results verification (see ***Sec. 8.3: Scientific Quality and Standardization***), and broadly improve research quality. The open sharing

[955] ORION. What Is Open Science? Accessed March 27, 2024. https://www.orion-openscience.eu/resources/open-science.

[956] White House. Fact Sheet: Biden-Harris Administration Announces New Actions to Advance Open and Equitable Research. The White House,. Accessed March 27, 2024. https://www.whitehouse.gov/ostp/news-updates/2023/01/11/fact-sheet-biden-harris-administration-announces-new-actions-to-advance-open-and-equitable-research/.

[957] Center for Open Science. Open Science Frammework (Osf) Home. Accessed March 27, 2024. https://osf.io/.

[958] Chin JM, McFadden R, Edmond G. Forensic Science Needs Registered Reports. *Forensic Science International: Synergy*. 2020; 2:41-5. doi:10.1016/j.fsisyn.2019.10.005.

[959] R Core Team. The R Project for Statistical Computing. R Foundation for Statistical Computing. Accessed March 27, 2024. https://www.r-project.org/.

[960] Cold Spring Harbor Laboratory. bioRxiv: The Preprint Server for Biology. Accessed March 26, 2024. https://www.biorxiv.org/.

[961] Nelson A. Memorandum for the Heads of Executive Departments and Agencies: Ensuring Free, Immediate, and Equitable Access to Federally Funded Research. Office of Science and Technology Policy, Executive Office of the President. Accessed March 27, 2024. https://www.whitehouse.gov/wp-content/uploads/2022/08/08-2022-OSTP-Public-Access-Memo.pdf

[962] Houck MM, Chin J, Swofford H, Gibb C. Registered Reports in Forensic Science. *Royal Society Open Science*. 2022; 9(11):221076. doi:10.1098/rsos.221076.

[963] Center for Open Science. Registered Reports: Peer Review before Results Are Known to Align Scientific Values and Practices. Accessed March 26, 2024. https://www.cos.io/initiatives/registered-reports.

of research can also help to reduce the duplication of effort, provide research continuity, and assist in the identification of research gaps and needs.[964]

Furthermore, making research articles, data, and methods openly accessible to research consumers also promotes multidisciplinary research collaborations—for example, among researchers and practitioners within forensic DNA analysis, across other forensic science disciplines, and between criminal justice partner disciplines (e.g., law, psychology). These collaborations have the potential to shed new light on existing problems; identify or resolve emerging operational challenges; create new methods, techniques, and technologies; provide an opportunity to share expertise and best practices; and advance current practices. Open and transparent research engagement within and outside of the forensic DNA discipline can also lead to more effective and efficient use of resources, thereby increasing the pace of scientific progress.[965]

Many universities and academics are embracing the benefits of Open Science; however, it is important to recognize that transparency also presents challenges in these contexts, some of which may be particularly acute for private research organizations. For instance, the implementation of Open Science practices such as preregistration may be time-consuming. Additionally, when research involves cutting-edge, not obvious, and patentable technologies, intellectual property concerns may be substantial and can result in limited access to licensed technologies, even for research purposes. One argument against full and immediate public disclosure of all new developments, therefore, is the perception that the development or discovery will be available to the broader community and competitors before the innovator can be rewarded for it. Furthermore, the sharing of data, particularly DNA profiles, raises crucial ethical, legal, and confidentiality issues that must be addressed.[966] Nevertheless, the OSTP launched a series of actions for 2023 to become the Year of Open Science, signaling the importance of this movement for providing greater and more equitable access to knowledge from key areas of scientific study.[967]

Recommendation 12.2: All individuals and entities involved in forensic DNA analysis research should participate in Open Science practices and take steps to promote the transparency and accessibility of that research.

[964] Houck MM, Chin J, Swofford H, Gibb C. Registered Reports in Forensic Science. *Royal Society Open Science*. 2022; 9(11):221076. doi:10.1098/rsos.221076.

[965] Woelfle M, Olliaro P, Todd MH. Open Science Is a Research Accelerator. *Nature Chemistry*. 2011; 3(10):745-8. doi:10.1038/nchem.1149.

[966] Allen C, Mehler DMA. Open Science Challenges, Benefits and Tips in Early Career and Beyond. *PLoS Biology*. 2019; 17(5):e3000246. doi:10.1371/journal.pbio.3000246.

[967] White House. Fact Sheet: Biden-Harris Administration Announces New Actions to Advance Open and Equitable Research. The White House,. Accessed March 27, 2024. https://www.whitehouse.gov/ostp/news-updates/2023/01/11/fact-sheet-biden-harris-administration-announces-new-actions-to-advance-open-and-equitable-research/.

12.3.2 Aligned Incentives for Research Engagement

Aligned research incentives are a set of policies and practices designed to create a culture that values high-quality research and encourages participation.[968] However, there may currently be a misalignment between research engagement and the available incentives for those producing and consuming research. That is, researchers are incentivized to produce research as one of their primary role functions; however, the incentives for participation in applied forensic DNA research may not be well-aligned to some of the ideals of a positive research culture. For example, the rewards for generating foundational and basic research in terms of funding, esteem, and publications are often higher than the benefits associated with incremental, operationally determined, and applied research. This means that there can be costs to the career advancement of researchers in academia and industry who prioritize collaborations with FSSPs and practitioners.

In addition, job insecurity, funding challenges, and the "publish or perish" mentality also act to reduce the rewards associated with information sharing and collaboration more generally. Where individuals and researchers rely on being the first or only holder of some knowledge or technique to justify their promotion or salary or to maintain the viability of their business, researchers may understandably have little enthusiasm for sharing their knowledge outside the traditionally restricting avenues for publication and information dissemination. Further, where researchers disseminate outside of the academic publishing industry using openly accessible methods, this can negatively impact traditional metrics of success (e.g., citations, impact factors), which can contribute to further job insecurity.

Different examples of incentive misalignment emerge for FSSPs and practitioners. Unlike in academic and other professional research contexts, analysts are generally not rewarded for participation in research activities—either by their FSSPs or their profession—as there are minimal financial or reputational benefits associated with such research engagement. For example, for practitioners who engage more actively in research collaborations, their consumption or dissemination may not be recognized or promoted in the same way that completing more casework might be. Similarly, there is often little reward or recognition for FSSPs who build a positive research culture. This means that the research incentives for FSSPs and analysts are often misaligned or nonexistent beyond the requirement to undertake internal method validation.

[968] Council of Australian University Librarians. Open Research Toolkit. Accessed March 26, 2024. https://caul.libguides.com/open-research-toolkit/incentives; Mellor D. Improving Norms in Research Culture to Incentivize Transparency and Rigor. *Educational Psychologist*. 2021; 56(2):122-31. doi:10.1080/00461520.2021.1902329.

Sabbaticals or other forms of professional leave may be necessary to provide practitioners who are pursuing research collaborations with the time and resources to meaningfully participate. However, FSSPs understandably may not wish to lose casework analysts. As a result, it is in the experience of the EWG that FSSP participation in research is often underfunded, underprioritized, and undervalued in and by FSSPs. This misalignment (e.g., limiting applied and collaborative research targeting operational needs, restricting awareness of cutting-edge technology and best-practice procedures) can have significant consequences for the field, leading to key knowledge gaps and delays in FSSPs procuring and implementing emerging technology (e.g., next-generation sequencing methods). By creating aligned research incentives, FSSP leadership can promote a culture of research that prioritizes routine consumption of and collaboration in high-quality, relevant, and impactful research to advance the discipline.

Overall, these examples demonstrate the vital need for a systems approach to tackle the misaligned research incentives for those involved in research across the field of forensic DNA analysis. Until the incentives align with the ideals of a positive research culture, the scientific health and integrity of forensic DNA analysis will continue to be undermined.

12.3.3 Increased Collaboration

There are many ways to undertake collaborative research (including internal validation) and expand research participation. For researchers and research institutions, this may include inviting FSSPs and practitioners to speak with researchers about the operational challenges they are encountering in the discipline; inviting practitioners to complete sabbaticals or study leave on-site at research institutions; or by providing professional development opportunities such as training in validation research skills, critical analysis of scientific studies, foundational legal principles, and awareness of human factors. The NFDTC that is proposed in ***Sec. 9.6: Recommendation for a National Forensic DNA Training Consortium*** is one example of a large-scale formalized collaboration of this type, but smaller, ad-hoc and bespoke forms could also be valuable. Existing degree programs training forensic scientists would also fall into this category.

FSSPs could engage in more collaboration by inviting speakers from other FSSPs, research groups, and institutions to share their research across basic and applied domains from a range of disciplines with relevance to forensic DNA analysis, which could include biological science, law, psychology, criminology, statistics, or management. Additional collaboration could involve FSSPs participating as research volunteers in studies, such as those necessary to understand the role of human factors in forensic DNA analysis. FSSPs could invite researchers to complete sabbaticals at FSSPs. Together, researchers and FSSPs could jointly apply for funding, particularly to take advantage of interdisciplinary and multidisciplinary funding schemes; share datasets or samples (e.g., samples or results from internal validation studies) (see ***Sec. 8.3: Scientific Quality and***

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Standardization); or develop and execute joint research projects where all parties benefit from the knowledge and other research products generated.

Despite this wide array of exciting possibilities, it is important to acknowledge that collaborative research—particularly joint research studies—can be challenging in the field of forensic DNA analysis for a range of reasons. For example, there is often a disconnect between researchers' and practitioners' interests and priorities. In many cases, even when FSSPs have dedicated research groups, these researchers may be physically disconnected from practitioners and not well-versed in the challenges encountered in casework. This gap can hinder the development of research questions that address practitioners' most pressing needs. Although some FSSPs are associated with a university that has research capabilities to aid practitioners specifically with casework questions (see **Callout Box 12.3**), most FSSPs in the United States (and some other jurisdictions) are situated under law enforcement parent agencies, further restraining the ability to foster research collaborations with external agencies and partners.

Furthermore, forensic DNA analysis is a highly specialized field, and the research interests of academic and professional researchers may not always align with the operational needs of practitioners. For example, researchers may focus on developing novel techniques or technologies with the potential to patent and publish for purposes of eventual translation, whereas practitioners may be more focused on incremental improvements to the speed, accuracy, and reliability of existing methods, which may not generate the income or outputs researchers require. A systems approach—including the government, industry, practitioner, and academic sectors as well as funding bodies, criminal justice partners, and end-users—is likely required to bridge this gap.

Overall, collaboration between these diverse sectors and groups can bring together complementary expertise and resources to address complex problems, accelerate progress, and ensure that practitioner needs are given appropriate regard in emerging research (e.g., the National Institute of Justice's [NIJ's] solicitation for Research and Evaluation for the Testing and Interpretation of Physical Evidence in Publicly Funded Forensic Laboratories,[969] see also **Callout Box 12.4**). However, establishing successful collaborations between these parties is not straightforward and often requires institution-level support. Each group involved in forensic DNA analysis has its own set of priorities, incentives, and constraints.

Effective collaboration requires an understanding of these differences and a willingness to work together toward a valued common goal. Additionally, building and sustaining collaborative partnerships requires investment in long-term relationships, clear communication, and shared

[969] National Institute of Justice (NIJ). NIJ FY24 Research and Evaluation for the Testing and Interpretation of Physical Evidence in Publicly Funded Forensic Laboratories. Accessed March 27, 2024. https://nij.ojp.gov/funding/opportunities/nij-fy24-public-labs.

decision-making. Ultimately, the success of research collaborations in forensic DNA analysis will depend on the willingness of all parties to work together and support each other in achieving their goals. Whole-system support for collaboration can help break down information silos between different sectors, promote knowledge sharing, and create an environment that fosters joint innovation and progress.

Callout Box 12.3: Examples and Opportunities for Research and Innovation in Operational FSSPs

Netherlands Forensic Institute (NFI)

NFI is an independently funded agency of the Ministry of Justice and Security in the Netherlands. With approximately 600 full-time equivalent staff members, NFI hosts more than 30 areas of forensic expertise, ranging from pathology, toxicology, and archeology to forensic statistics, digital forensics, chemistry, and DNA. NFI has a mandate to perform three core tasks—casework, research and development (R&D) and innovation, and education. NFI's resources are devoted roughly 70% to casework, 20% to R&D and innovation, and 10% to education.

NFI has a strategic research agenda that focuses on three levels of R&D and innovation:

1. Fostering and developing the "ecosystem" of monodisciplinary research and development is important to ensure that the fields remain state-of-the-art. The different forensic disciplines work with research agendas and prioritized themes to focus their R&D efforts.
2. A strong emphasis has been placed on multidisciplinary research and innovation, involving multiple forensic disciplines to address current and future forensic challenges that are relevant for most disciplines.
3. A third focal point for research and innovation is the entire forensic chain from "crime scene to courtroom." Joint projects between partners in the criminal justice system strengthen the forensic chain as a whole.

Examples of projects in the three pillars of the strategic research agenda can be found on NFI's website.[970]

The interplay between NFI's three core tasks is essential in creating a cycle in which the (future) forensic services remain relevant and applicable for the end-users. NFI therefore encourages its scientists to actively participate in research projects in order to benefit from the "pull" of operational forensic practice; current casework needs strongly drive R&D within the teams. This involvement in research is also a crucial aspect to the professional development of NFI staff.

The "push" of new technologies and developments—from academia and the private sector—inspires innovation in the forensic sciences. Many technologies and knowledge that are of potential relevance to forensic applications are developed in different fields, such as medical sciences or agricultural sciences. NFI historically has a strong link with academia, which is strengthened by senior NFI scientists being appointed to (part-time) professorships at different universities in the Netherlands. Currently NFI has 12 professors appointed to seven universities. These appointed senior NFI scientists bridge the gap between operational forensic practice and scientific innovation in academia, while also being actively involved in the education of the next generation of forensic scientists through bachelor and master programs at the seven Dutch universities.

Further external collaboration is actively sought. Over the last few years, NFI has signed a Memorandum of Understanding with the Delft University of Technology, Leiden University of Applied

[970] Netherlands Forensic Institute. Research and Innovation. Netherlands Forensic Institute, Ministry of Justice and Security. Accessed March 27, 2024. https://www.forensicinstitute.nl/research-and-innovation.

Sciences, and the University of Lausanne to further stimulate and reinforce academic cooperation. Furthermore, NFI is one of the founding partners of The Co van Ledden-Hulsebosch Center (CLHC), the Amsterdam Center for Forensic Science and Medicine of the University of Amsterdam. CLHC represents a dynamic and diverse forensic network in the Netherlands connecting science domains, forensic expertise areas, and academic scholars and experts from the criminal justice system including legal professions. Finally, NFI is one of the founders and an active member of the European Network of Forensic Science Institutes (ENFSI).

To maintain and, where possible, strengthen the innovative position of NFI, NFI scientists affiliate and are actively involved with national and international funding acquisition and other initiatives. These research consortia are financed by various national and international subsidy providers, such as ENFSI, the Dutch Research Council, and European subsidy programs. This external funding of R&D activities is essential for a balanced and innovative project portfolio. External project acquisition is essential for NFI to initiate scientific research focusing on the opportunities presented by the latest technological and social developments.

The governance of R&D and innovation at NFI is an interplay of (1) internal resource management, (2) scientific grounding, and (3) external needs and opportunities. Some examples of governance bodies and organizational support that help NFI achieve an optimal outcome are an internal and an external scientific advisory board, a criminal justice system innovation steering group, a Ministry of Justice and Security innovation board, a team of principal scientists, and an R&D project support desk.

Being both an operational FSSP and a research and knowledge center with scientists committed to both tasks is a distinct advantage, but also presents a major challenge in balancing the daily pull of urgent casework and the attention to longer-term R&D. This balance needs to be actively maintained, which requires scientists, institute management, and criminal justice system and other external partners to have a shared understanding of the need for innovation and R&D and to recognize the crucial role that FSSPs have in the innovation and implementation of new knowledge and technology. Striking this balance will drive a healthy research culture in the forensic sciences.

Marshall University

Marshall University's Technical Assistance Program (TAP)[971] is a service provided by the Marshall University Forensic Science Graduate Program for accredited FSSPs across the United States and the globe. The service aims to provide graduate students with access to cutting-edge forensic technology and processes while promoting collaborative research opportunities in FSSPs.

FSSPs request technical assistance for a validation or research proposal involving new instrumentation, software, or process they are considering. The program requires the addition of a research component beyond a validation request that will serve the FSSP's mission and goals as well as those of the forensic science community. TAP facilitates communication between the FSSP and student to develop the full validation/research proposal. Equipped with specific training and a research proposal, the student performs the research experiments and data collection on-site at the FSSP. The research is often submitted for publication or presentation at professional forensic meetings.

TAP provides a range of benefits to both students and the FSSP employing this resource. This program brings research to FSSPs and helps disseminate research to the forensic community through presentations and publications. It encourages and grows a research culture for both the student and FSSP, establishing the importance and technical skills of the research at an early point in students' forensic careers and bringing research opportunities to FSSPs that otherwise have not made casework a priority because of case workloads.

[971] Marshall University. Forensic Science Graduate Program: DNA Technical Leader Assistance Program (TAP). Accessed March 27, 2024. https://www.marshall.edu/forensics/tap.

TAP requires careful communication, planning, and coordination between Marshall University, the student, and the host FSSP. Additionally, there are time constraints surrounding the research performed by the student, which can limit both the scope and complexity of the research proposal. Despite these challenges, FSSPs using TAP can gain research, validation, and evaluation of new technology and processes with minimum impact on the production environment. Often this research leads to the implementation of new methods, increasing FSSPs' productivity. FSSPs and DNA analysts build scientific stature and are further immersed in the broader research culture, ultimately strengthening the forensic community.

12.3.4 Research Funding

The current funding for forensic DNA research offers a mix of opportunities and challenges. On one hand, there has been significant investment in the field (for example, see **Callout Box 12.4**) over the past several decades, resulting in numerous advances in technology and methodology.[972] Some of this investment has led to the development of increasingly sensitive and accurate DNA analysis methods. However, there are also ongoing challenges related to funding that can impact the ability of researchers and FSSPs to conduct and maintain access to research in this constantly evolving field.

One of the primary challenges facing forensic DNA research is the limited availability of funding sources that can serve research funding needs. As already discussed, research and research resources are costly, including those provided as part of practitioner education and professional development (see ***Sec. 9.5*: *Continuing Education***). Although federal and state governments have historically been major funders of forensic DNA research projects, budget cuts and shifting priorities can make it increasingly difficult for researchers to secure the resources they need to conduct high-quality research. Additionally, many private foundations and other nongovernmental organizations may not have a specific interest in forensic DNA analysis, further limiting funding opportunities for researchers in the field. In addition, there are few external funding resources FSSPs could use to purchase research materials, provide study leave, or take on additional staff to increase the time and opportunity for research participation among casework analysts.

Even when funding is available in principle, it is often not straightforward for interested parties to identify applicable funding sources. Moreover, researchers and FSSPs are likely to have different skills and experience when it comes to writing competitive funding requests and grant proposals for different types of funders. When and if funding is obtained, it is often not trivial to manage and acquire the research funds—particularly when that funding is obtained through interdisciplinary schemes or across sectors. As a result, opportunities for research groups and

[972] Forensic Technology Center of Excellence (FTCoE). NIJ R&D Success Stories. National Institute of Justice, Office of Justice Programs, U.S. Department of Justice. Accessed March 27, 2024. https://forensiccoe.org/nij-success-stories/.

FSSPs to successfully identify, obtain, and reconcile the funds needed to conduct, consume, and collaborate in research may be lost.

Callout Box 12.4: Example Research Funding Opportunity: NIJ

Starting in 2015, NIJ initiated an annual solicitation specifically aimed at providing funding to public FSSPs titled Research and Evaluation for the Testing and Interpretation of Physical Evidence in Publicly Funded Forensic Laboratories.[973] The goal of this solicitation is to support research to evaluate current laboratory methods or emerging methods. Under this solicitation, awards produce deliverables that include best practices to improve efficiency, accuracy, reliability, and cost-effectiveness as well as protocols that can be adopted by the community.

Over the last eight years, this solicitation has provided funding for research to evaluate or improve DNA methods including massive parallel sequencing (also called next-generation sequencing), body fluid identification, mixture interpretation, and sexual assault evidence selection. Through this solicitation, NIJ provides resources to encourage FSSPs' engagement with research and contributions toward building a positive research culture within the forensic sciences and to assure improvements to both scientific integrity and quality within the forensic DNA discipline.

12.4 Research Priorities

A key driver of successful collaboration within a positive research culture is shared vision and understanding of the research gaps and needs in the area. The 2009 National Academy of Sciences (NAS) Report noted an absence of a coordinated system for establishing priorities and directions for research in forensic science.[974] NIJ recently responded to this call in its 2022–2026 Forensic Science Strategic Research Plan by laying out five strategic research priorities and identifying NIJ as "a coordination point within the forensic science community to help meet the challenges caused by high demand and limited resources."[975]

The five strategic priorities that NIJ identified are:

- Advance applied research and development in forensic science.
- Support foundational research in forensic science.
- Maximize the impact of forensic science research and development.
- Cultivate a diverse, highly skilled forensic science workforce.
- Coordinate across the community of practice.

[973] National Institute of Justice (NIJ). NIJ FY24 Research and Evaluation for the Testing and Interpretation of Physical Evidence in Publicly Funded Forensic Laboratories. Accessed March 27, 2024. https://nij.ojp.gov/funding/opportunities/nij-fy24-public-labs.

[974] National Research Council, Committee on Identifying the Needs of the Forensic Science Community. *Strengthening Forensic Science in the United States: A Path Forward*. The National Academies Press: Washington, DC, 2009. doi:10.21428/cb6ab371.b2d683d2.

[975] National Institute of Justice (NIJ). Forensic Science Strategic Research Plan, 2022-2026. Accessed March 27, 2024. https://nij.ojp.gov/topics/articles/forensic-sciences-strategic-research-plan-2022-2026#strategic-priority-iv-cultivate-a-diverse-highly-skilled-forensi. *See* Strategic Priority V: Coordinate Across the Community of Practice, p. 17.

In total, there are 23 research objectives spread across these five strategic priorities. Most of these objectives have the potential to contribute to a more positive research culture for forensic DNA analysis in some way. Examples of these objectives include promoting innovative and foundational research, advocating for diverse forms of research including later-stage applied and transitional projects, supporting research openness and transparency, seeking processes to support diversity and inclusion, highlighting the value of collaboration and teamwork, addressing research integrity and professionalism, and focusing on continuous education.[976]

We support a coordinated research approach, such as the one put forth by NIJ, and advocate the establishment of a nonregulatory federal agency to provide leadership and resources to build and maintain a positive research culture in forensic DNA analysis. Furthermore, the overlap between the NIJ research objectives and the key elements of a positive research culture underscores the significant role of a positive research culture in the future of forensic science.

12.5 List of Research Needs Related to Human Factors in Forensic DNA Interpretation

The following is a non-exhaustive list of research needs identified and developed by the EWG throughout the course of our scientific assessment to further enhance the understanding of human factors considerations in forensic DNA interpretation.

- What factors play into the acceptance or rejection of software-assisted profile interpretations?
- Are DNA analysts more likely to accept a PGS interpretation with an out-of-range diagnostic for complex mixture profiles, where the anticipated genotype combinations may be harder to intuit, simply because the analyst has no other means by which to interpret such a profile?
  - Can a standardized framework be developed for determining what FSSPs should consider within-range and out-of-range?
- How do significant case backlogs, short turnaround times for analysis, or high-profile cases influence DNA interpretation decisions?
- What is the level of inter- and intra-variability of FSSPs when assigning number of contributors? What contributes to this variability?
- How do laypersons understand the likelihood ratio (LR), and what is the impact of prior beliefs on final decisions that incorporate the LR?
- What are effective training techniques to improve scientists' and laypersons' understanding of LRs?

[976] Ibid.

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- Do verbal qualifiers improve comprehension of DNA results? Should the entire scale be presented, or just the qualifier and the numerical range for the actual LR expressed?
- What is the prevalence of current DNA analysts transposing the conditional, and what impact does this have on outcomes in a case?
- Are DNA analysts able to reliably evaluate DNA results given activity-level propositions?
- How often is problematic activity-level testimony introduced in court, and how far does such testimony stray from best practices or what current research can support?
  - What is the impact of this testimony on the case decision?
  - What is the impact of this testimony on juror comprehension?
- How does general versus case-specific information about DNA transfer, persistence, prevalence, and recovery (DNA-TPPR) during testimony impact factfinders' decision-making?
- What are the impacts of an expert providing a categorical opinion about the source of the DNA versus a probabilistic opinion?
- What are the impacts of an expert providing limitations, caveats, and error rates on factfinders' decision-making?
- How effective are blind proficiency tests to assess the overall quality of a system? Does blinding a proficiency test increase detection of errors when compared with non-blind proficiency testing?
- What is the cost-benefit ratio for blind versus non-blind proficiency testing?
- What is the cost-benefit ratio for blind versus non-blind technical review?
- How effective is a linear sequential unmasking procedure for mitigating the potential for cognitive bias in DNA comparisons?
- What human factors influence nonconformities in forensic DNA analysis?
- What support do FSSPs need for the ethical collection and open-access publishing and sharing of validation data for DNA profiles?
- How effective are quality assurance/quality control (QA/QC) processes (e.g., peer review, proficiency testing) at minimizing cognitive bias and error?
- How prevalent are stressors and traumas associated with forensic science professionals (e.g., vicarious trauma, compassion fatigue, secondary traumatic stress, burnout) and what are their impacts on overall employee wellness and job performance?
- What is the impact of institutional separation (i.e., autonomy of an FSSP from a parent organization) on overall FSSP culture?
- Is institutional separation a predictor of a culture of FSSP independence?

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- What is the most task-appropriate lighting condition for visual tasks that DNA analysts perform at workbenches and in laboratory workspaces?
- Does knowing that your testimony is being evaluated impact performance?
- Does having a peer or supervisor present during testimony improve or inhibit performance?
- What is the efficacy of an internal peer review over an external review?
- Is there more potential to identify systemic errors in testimony through external reviews or internal reviews?

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13. Summary of Recommendations

Recommendations that did not reach consensus are marked with an asterisk. Dissenting or qualified support statements are presented in corresponding footnotes in their relevant sections. Recommendations should be read and understood in the context of their surrounding material.

Recommendation 3.1: To promote balance and transparency in DNA analysis, forensic science service providers should apply the "principles of interpretation" and should understand the "hierarchy of propositions."

Recommendation 3.2: DNA analysts should maintain a detailed record of the reasoning, justification, and sequence of decisions not dictated by the forensic science service provider's protocols (i.e., discretionary decisions).

Recommendation 3.3: Forensic science service providers should assess their processes to identify potential sources of bias in the interpretation and comparison of DNA evidence. Forensic science service providers should implement written policies and procedures to mitigate these sources of bias.

Recommendation 3.4: Forensic science service providers should evaluate and understand the impact that procedural decisions have on DNA results and their interpretation. With this knowledge, DNA analysts should be able to understand the effect certain treatments will have on downstream decisions and outcomes within the DNA analysis workflow.

Recommendation 3.5: Forensic science service providers should validate and apply analysis settings and laboratory processes that generate and characterize as much informative data as possible with the available instrumentation and technology.

Recommendation 3.6: To reduce the variability in how DNA analysts determine profile suitability, forensic science service providers should validate, set, implement, and routinely reassess suitability boundaries.

Recommendation 3.7: Forensic science service providers should validate and apply interpretation methods that take into account all data necessary to help address the propositions. Currently, for the interpretation of DNA comparisons, continuous probabilistic genotyping is the only interpretation technique that meets this criterion.

Recommendation 3.8: Forensic science service providers' standard operating procedures should provide criteria for assessing and documenting when a probabilistic genotyping interpretation should be rejected.

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Recommendation 3.9: DNA analysts should not modify an original interpretation decision based on the Person of Interest's profile, except in very limited circumstances. Forensic science service providers should have clear protocols describing the circumstances under which a reevaluation is allowable, and documentation must alert the end-user that these changes occurred post-comparison.

Recommendation 4.1: Forensic science service providers should use likelihood ratios to evaluate DNA results.

Recommendation 4.2: To avoid conveying an unsupported level of precision, forensic science service providers should express likelihood ratios as an order of magnitude or to one significant figure.

Recommendation 4.3: To avoid presenting likelihood ratios that are larger than can be supported by currently available research and to assist in the comprehension of analyses that result in very large likelihood ratios (or very small Random Match Probabilities) with respect to unrelated individuals, forensic science service providers should implement a reporting cap of 1 billion (or 1 in 1 billion), or an alternative value that can be justified by research.*

Recommendation 4.4: To make likelihood ratio values less than 1 (e.g., 0.00001 or 1/100,000) easier to comprehend, forensic science service providers can reverse the propositions, which will invert the LR (e.g., 100,000). If doing so, analysts must clearly report that they have reversed the propositions for this purpose. The original likelihood ratio must be available in the case file.

Recommendation 4.5: DNA analysts should state the likelihood ratio value rather than using qualitative terms that end-users can misunderstand, such as "match," "included," "consistent with," and "cannot be excluded." It is acceptable to use the term "excluded" if the DNA analyst is transparent about how they reached that opinion and outlines the limitations of such an opinion.

Recommendation 5.1: To help reduce the risk of tunnel vision and confirmation bias in an investigation, forensic science service providers should report the limitations of DNA database searches to law enforcement investigators, including that associations can occur with individuals who are not the source of the DNA.

Recommendation 5.2: To reduce the potential for being misunderstood, DNA reports should contain clear, concise, and unbiased language. Terms such as major contributor and sperm fraction may be misinterpreted as indicating the nature of the biological material and how or by whom the DNA was deposited. If the report contains any such terms, it should include the limitations of those terms.

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Recommendation 5.3: Forensic science service providers should include caveats and limitations in reports containing an evaluation of results considering the source of the DNA. These should make clear that:

- If any conditioning information used in the calculation changes, a new evaluation is needed.
- The evaluation of the DNA comparison cannot conclusively identify an individual as the source of the DNA.
- The report does not provide any information about how or when the DNA was deposited.

Recommendation 5.4: Forensic science service providers should offer training to criminal justice partners on the caveats and limitations of DNA testing so that results are properly incorporated along with other information in the case.

Recommendation 6.1: When legally permissible and possible, the testifying DNA analyst and the legal professionals involved in the case should confer prior to the trial to gain a shared understanding of the report, propositions, correct language for describing the value of the results, and what the results mean and do not mean.

Recommendation 6.2: When explaining the nature of DNA analysis during testimony, the DNA expert should address common misconceptions and state the limitations of the analysis. At a minimum, the DNA expert should address the following main points:

- The DNA results are only part of the overall case.
- Errors can occur in any human process, including DNA analysis.
- The evaluation of the DNA comparison cannot conclusively identify an individual as the source of the DNA.
- DNA analysts cannot provide any information on how or when DNA was deposited in a particular case, based on a report considering only the source of the DNA.

Recommendation 6.3: DNA experts should not perform new evaluations of the DNA results on the witness stand because these evaluations have not been reviewed, reported, or disclosed to all parties.

Recommendation 7.1: DNA analysts should not opine about the possibility or probability of direct or indirect transfer having occurred in a case.*

Recommendation 7.2: The evaluation of DNA results given "how" and "when" questions is distinct from the evaluation of DNA results given "who" questions. In order to develop policies and practices on how DNA analysts should respond appropriately to questions about how and when DNA was deposited in a particular case, forensic science service providers should consult professional guidance and experts who understand issues related to transfer and persistence.

These policies and practices should require DNA analysts to be appropriately trained to respond to such questions.*

Recommendation 7.3: The federal government should fund collaborative efforts to review the foundations and principles of evaluating biological results when considering alleged activities. Based on the findings, additional fiscal support should be available to educate and guide DNA and legal communities on the review, research, selection, and validation of appropriate methods to account for DNA transfer, persistence, prevalence, and recovery when assessing biological results.

Recommendation 8.1: Teams of at least two individuals from different organizations or with different types or levels of experience in forensic biology should conduct external assessments of forensic DNA laboratories.

Recommendation 8.2: To increase transparency, collaboration, and communication, the forensic DNA community should support and expand development of each of the following:

- An open-access internal validation data repository that allows forensic science service providers to share validation methods, findings, and data. This repository could be curated by a federal nonregulatory agency that has capabilities in measurement science, statistics, DNA analysis, and data management.
- Procedures for the ethical collection of DNA samples by forensic science service providers for research and validation studies and subsequent collection and use of these samples within the open-access validation data repository.
- An ethically collected, standardized subset of samples that can aid in facilitating validation work and be uploaded to the open-access internal validation data repository.

Recommendation 8.3: When possible and legally permissible, forensic science service providers should promote the development, maintenance, and use of elimination databases containing DNA profiles from forensic science service provider personnel and other personnel (e.g., crime scene technicians, law enforcement investigators, and emergency responders) who may come into contact with evidence or samples that are collected for DNA testing. Forensic science service providers should search unknown profiles against this elimination database before reporting or uploading to other forensic or reference sample databases.*

Recommendation 8.4: To maximize the potential to detect errors and omissions, forensic science service providers should ensure that technical review processes include steps to mitigate review bias, direct attention to important decisions for review, consider fatigue, consider difficult case reviews, and identify appropriate methods to resolve and document disagreements.

Recommendation 8.5: To regularly monitor performance, forensic science service providers should assess both system and individual performance through internal or external testing regimes that reflect the range of complexity encountered and the procedures used in casework.

Recommendation 8.6: Forensic science service providers should provide analysts with training exercises at intervals related to task complexity. These exercises should comprise a variety of difficult, error-prone, and uninterpretable samples, in which analysts receive feedback in a nonpunitive training environment to further develop and maintain their expertise.

Recommendation 8.7: To improve consistency and reduce the potential for subjective or biased assessments, forensic science service providers should use a risk-based approach with documented guidance in the investigation and resolution of nonconformities. At minimum, a matrix or defined categories should be used to assess the risk of the nonconformity occurring or recurring and its impact on casework.

Recommendation 9.1: In addition to technical competency, forensic science service providers should require DNA analysts and DNA Technical Leaders to demonstrate understanding of the following subject areas, as appropriate to their role:

- Human factors in forensic DNA analysis and interpretation
- Root-cause analysis
- Professional responsibility under applicable Codes of Conduct
- Constitutional, statutory, and other disclosure obligations
- How to maintain independence and avoid errors during testimony
- How to communicate forensic statistical concepts and scientific limitations to factfinders

Recommendation 9.2: To reduce variability in education and training practices and increase quality and consistency of forensic DNA testing and interpretation, a federal nonregulatory agency or nonprofit organization should develop a National Forensic DNA Training Consortium with the mission to provide standardized and high-quality education and training for technical (e.g., DNA analysts, DNA Technical Leaders) and quality assurance personnel. This National Forensic DNA Training Consortium should offer the training needed for new forensic science service provider personnel as well as continuing education opportunities. Both offerings should include assessment components, written and practical as appropriate.

Recommendation 10.1: In addition to the necessary technical qualifications, the DNA Technical Leader should have the knowledge, skills, and abilities to serve in a leadership capacity within the forensic science service provider. Parent organizations and forensic science service providers should continually support and dedicate resources (e.g., funding, time) to DNA Administrative

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Supervisors and DNA Technical Leaders to participate in managerial and leadership programs that further develop their leadership knowledge, skills, and abilities.

Recommendation 10.2: Forensic science service provider management should clearly define the roles, responsibilities, and authorities of DNA Administrative Supervisor and DNA Technical Leader positions. Management should dedicate leadership resources to each role and communicate the definition of these roles to all individuals who are employed by, or work closely with, the forensic science service provider to help clarify reporting structures and enable the individuals to fulfill their responsibilities. Ideally, because of the difference in responsibilities between DNA Administrative Supervisors and DNA Technical Leaders, different individuals should hold these positions.

Recommendation 10.3: Parent organization leadership and criminal justice partners who regularly interact with the forensic science service provider should understand laboratory best practices in order to accurately represent the scientific evidence and capabilities of the laboratory, reduce the risk of the parent organizations or criminal justice partners exerting undue influence on DNA analysts, and appropriately allocate funding and resources for forensic science service provider operations. To inform this understanding, forensic science service providers should offer regular training to parent organization leadership and criminal justice partners on the following topics:

- Quality systems
- Accreditation
- Undue influence
- Scientific limitations
- Laboratory reports
- Laboratory operations
- Laboratory leadership
- Laboratory independence
- Principles of interpretation
- Changes to laboratory practices
- Cognitive bias and contextual information management procedures

Recommendation 10.4: DNA Administrative Supervisors and DNA Technical Leaders manage complex scientific and business operations. To continually improve the organization's performance, these leaders should actively engage in essential business practices of operational management, including strategic planning, process improvements, human resource management, succession planning, quality management, and criminal justice partnerships.

Recommendation 10.5: Forensic science service provider management and parent organizations should support, facilitate, and provide ongoing opportunities for their personnel to improve mental health and wellness, including addressing vicarious trauma, stress, and burnout. Management should:

- Understand how these issues harm forensic science service provider personnel.
- Understand their and the organization's role in contributing to and mitigating workplace stress and burnout.
- Encourage DNA analysts to engage in employee wellness opportunities.

Recommendation 11.1: Forensic science service provider management, alongside DNA analysts and support personnel, should explore techniques to mitigate noise levels. These techniques could include the use of temporary quiet workspaces, dedicated collaboration spaces, or designated quiet times.

Recommendation 11.2: Forensic science service provider management should afford DNA analysts and support personnel the opportunity to reserve time and space for task-appropriate functions such as a conference room for case reviews or dedicated calendar times to limit task interruptions in the workplace.

Recommendation 11.3: To optimize user performance and satisfaction, forensic science service provider management and laboratory designers should seek input from DNA analysts to evaluate the usability and accessibility of physical work environment configurations and technologies before they are designed and implemented.

Recommendation 11.4: To prevent and detect handling errors when multiple DNA analysts participate in the processing of samples, forensic science service providers should have communication and coordination strategies that require transparency, continual training, and proficiency.

Recommendation 12.1: To support a positive research culture, forensic science service providers should ensure that DNA analysts have access to, and are supported to engage with, current and emerging scholarship and technologies. This may be achieved by providing opportunities and resources for analysts to be involved in journal clubs, attend scientific presentations or conferences, work collaboratively with academic and industry partners, lead or participate in workgroups or training, or participate in validation or research projects supported by the forensic science service provider.

Recommendation 12.2: All individuals and entities involved in forensic DNA analysis research should participate in Open Science practices and take steps to promote the transparency and accessibility of that research.

References

Abbott TEF, Ahmad T, Phull MK, Fowler AJ, Hewson R, Biccard BM, Chew MS, Gillies M, Pearse RM, International Surgical Outcomes Study g. The Surgical Safety Checklist and Patient Outcomes after Surgery: A Prospective Observational Cohort Study, Systematic Review and Meta-Analysis. *British Journal of Anaesthesia*. 2018; 120(1):146-55. doi:10.1016/j.bja.2017.08.002.

Aerossurance. 'Procedural Drift': Lynx CFIT in Afghanistan. Accessed March 23, 2024. https://aerossurance.com/helicopters/procedural-drift-lynx-cfit/.

Aitken C, Berger CEH, Buckleton J, Champod C, Curran JM, Dawid AP, Evett IW, Gill P, Gonzalez-Rodriguez J, Jackson G, Kloosterman A, Lovelock T, Lucy D, Margot P, McKenna L, Meuwly D, Neumann C, Daeid NN, Nordgaard A, Puch-Solis R, Rasmusson B, Redmayne M, Roberts P, Robertson B, Roux C, Sjerps MJ, Taroni F, Tjin-A-Tsoi T, Vignaux GA, Willis SM, Zadora G. Expressing Evaluative Opinions: A Position Statement. *Science & Justice*. 2011; 51(1):1-2. doi:10.1016/j.scijus.2011.01.002.

Aitken C, Stoney DA. *The Use of Statistics in Forensic Science*. Taylor & Francis: London, UK, 1991. doi:10.1201/b12618.

Aitken C, Taroni F. *Statistics and the Evaluation of Evidence for Forensic Scientists*. 2nd ed. John Wiley & Sons, Ltd: West Sussex, UK, 2004. doi:10.2307/1268932.

Aitken C, Taroni F. A Verbal Scale for the Interpretation of Evidence. *Science & Justice*. 1998; 38(4):279-281. doi:10.1016/S1355-0306(98)72128-8.

Aitken C, Taroni F, Bozza S. *Statistics and the Evaluation of Evidence for Forensic Scientists*. 3rd ed. John Wiley & Sons, Ltd: Hoboken, NJ, 2021.

Allen C, Mehler DMA. Open Science Challenges, Benefits and Tips in Early Career and Beyond. *PLoS Biology*. 2019; 17(5):e3000246. doi:10.1371/journal.pbio.3000246.

Almazrouei MA, Dror IE, Morgan RM. The Forensic Disclosure Model: What Should Be Disclosed to, and by, Forensic Experts? *International Journal of Law, Crime and Justice*. 2019; 59:100330. doi:10.1016/j.ijlcj.2019.05.003.

Almazrouei MA, Dror IE, Morgan RM. Organizational and Human Factors Affecting Forensic Decision-Making: Workplace Stress and Feedback. *Journal of Forensic Sciences*. 2020; 65(6):1968-77. doi:10.1111/1556-4029.14542.

Alter AL, Oppenheimer DM. Uniting the Tribes of Fluency to Form a Metacognitive Nation. *Personality and Social Psychology Review*. 2009; 13(3):219-35. doi:10.1177/1088868309341564.

American Academy of Forensic Sciences. Forensic Science Education Programs Accreditation Commission. Accessed March 23, 2024. https://www.aafs.org/FEPAC.

American Academy of Forensic Sciences. SWGDAM Notice on QAS Educational Requirements. Accessed March 23, 2024. https://www.aafs.org/article/swgdam-notice-qas-

educational-requirements?utm_source=swgdam-notice&utm_medium=email&utm_campaign=dec-9-newsletter.

American Academy of Forensic Sciences Standards Board. *ANSI/ASB Standard 115: Standard for Training in Forensic Short Tandem Repeat Typing Methods Using Amplification, DNA Separation, and Allele Detection*. 2020. https://www.aafs.org/sites/default/files/media/documents/115_Std_e1.pdf.

American Academy of Forensic Sciences Standards Board. *ASB Standard 041, First Edition 2021: Formulating Propositions for Likelihood Ratios in Forensic DNA Interpretations*. 2021. https://www.aafs.org/sites/default/files/media/documents/041_Std_Ballot02.pdf

American Academy of Forensic Sciences Standards Board. *ASB Standard 139, First Edition 2022: Reporting DNA Conclusions*. 2022. https://www.aafs.org/sites/default/files/media/documents/139_Std_Ballot02.pdf.

American Association for Laboratory Accreditation (A2LA). Forensic Examination Accreditation Program. Accessed March 23, 2024. https://a2la.org/accreditation/forensics/.

American Bar Association. *ABA Standards for Criminal Justice: Discovery, Fourth Edition*. PART II Discovery Obligations of The Prosecution and Defense. 2020. https://www.americanbar.org/groups/criminal_justice/standards/discovery-fourth-edition/.

American Board of Criminalistics. *ABC Rules of Professional Conduct*. 2016. https://www.criminalistics.com/uploads/3/2/3/3/32334973/09-0001f_v1.0.1_abc_rules_of_professional_conduct.pdf.

American Board of Criminalistics. American Board of Criminalistics History. Accessed March 23, 2024. https://www.criminalistics.com/history.html.

American Board of Criminalistics. Certification. Accessed March 23, 2024. https://www.criminalistics.com/certification.html.

American Board of Criminalistics. Forensic DNA Examination. Accessed March 23, 2024. https://www.criminalistics.com/forensic-dna.html.

American Board of Criminalistics. *Recertification Point Structure*. 2020. https://www.criminalistics.com/uploads/3/2/3/3/32334973/recertification_point_structure.pdf.

American Heart Association. Why Is Physical Activity So Important for Health and Well-Being? Accessed March 23, 2024. https://www.heart.org/en/healthy-living/fitness/fitness-basics/why-is-physical-activity-so-important-for-health-and-wellbeing.

American National Standards Institute/Academy Standards Board. *ANSI/ASB Standard 020: Standard for Validation Studies of DNA Mixtures, and Development and Verification of a Laboratory's Mixture Interpretation Protocol*. 2018. https://www.aafs.org/sites/default/files/media/documents/020_Std_e1.pdf.

This publication is available free of charge from: https://doi.org/10.6028/NIST.IR.8503

American National Standards Institute/Academy Standards Board. *ANSI/ASB Standard 022: Standard for Forensic DNA Analysis Training Programs*. 2019. https://www.aafs.org/sites/default/files/media/documents/022_Std_e1.pdf.

American National Standards Institute/Academy Standards Board. *ANSI/ASB Standard 040: Standard for Forensic DNA Interpretation and Comparison Protocols*. 2019. https://www.aafs.org/sites/default/files/media/documents/Std_040_e1.pdf.

American Psychological Association. Particularly Exciting Experiments in Psychology - Heuristics. Accessed March 23, 2024. https://www.apa.org/pubs/highlights/peeps/issue-105.

American Society for Quality. What Is a Quality Management System (QMS)? Accessed March 23, 2024. https://asq.org/quality-resources/quality-management-system.

American Society of Heating, Refrigerating and Air-Conditioning Engineers Inc. (ASHRAE), American National Standards Institute. *ANSI/ASHRAE Standard 55-2023—Thermal Environmental Conditions for Human Occupancy*. 2023. https://www.ashrae.org/technical-resources/bookstore/standard-55-thermal-environmental-conditions-for-human-occupancy.

ANSI National Accreditation Board (ANAB). *Accreditation Manual for Forensic Laboratories, Forensic Inspection Bodies, and Property and Evidence Control Units*. 2024. https://anab.qualtraxcloud.com/ShowDocument.aspx?ID=7183.

ANSI National Accreditation Board (ANAB). *AR 3125: Accreditation Requirements for Forensic Testing and Calibration (2023)*. 2023. https://anab.qualtraxcloud.com/ShowDocument.aspx?ID=12371.

ANSI National Accreditation Board (ANAB). Personnel Certification under ISO/IEC 17024: American Board of Criminalistics, Inc. Accessed March 23, 2024. https://anabpd.ansi.org/Accreditation/credentialing/personnel-certification/AllDirectoryDetails?&prgID=201&OrgId=152501&statusID=4.

Antonsen S, Almklov P, Fenstad J. Reducing the Gap between Procedures and Practice - Lessons from a Successful Safety Intervention. *Safety Science Monitor*. 2008; 12(1):1-16.

Archer MS, Wallman JF. Context Effects in Forensic Entomology and Use of Sequential Unmasking in Casework. *Journal of Forensic Sciences*. 2016; 61(5):1270-7. doi:10.1111/1556-4029.13139.

Association of Firearm and Tool Mark Examiners (AFTE). AFTE Certification. Accessed March 23, 2024. https://afte.org/afte-certification.

ASTM International. *ASTM E2916-19e1: Standard Terminology for Digital and Multimedia Evidence Examination*. 2019. https://www.astm.org/e2916-19e01.html.

ASTM International. *ASTM E2917-19a: Standard Practice for Forensic Science Practitioner Training, Continuing Education, and Professional Development Programs*. 2022. https://www.astm.org/e2917-19a.html.

ASTM International. Homepage. Accessed March 23, 2024. https://www.astm.org/.

This publication is available free of charge from: https://doi.org/10.6028/NIST.IR.8503

Australian Academy of Science. Open Science and Scientific Excellence. Accessed May 19, 2023. https://www.science.org.au/curious/policy-features/open-science-and-scientific-excellence.

Balding DJ, Steele CD. *Weight-of-Evidence for Forensic DNA Profiles*. 2nd ed. John Wiley & Sons, Ltd: West Sussex, UK, 2015. doi:10.1002/9781118814512.

Baldwin DP, Bajic SJ, Morris M, Zamzow D. *A Study of False-Positive and False-Negative Error Rates in Cartridge Case Comparisons*. Ames Laboratory, USDOE. 2014. https://www.ojp.gov/pdffiles1/nij/249874.pdf.

Ballantyne KN, Edmond G, Found B. Peer Review in Forensic Science. *Forensic Science International*. 2017; 277:66-76. doi:10.1016/j.forsciint.2017.05.020.

Banbury SP, Berry DC. Office Noise and Employee Concentration: Identifying Causes of Disruption and Potential Improvements. *Ergonomics*. 2005; 48(1):25-37. doi:10.1080/00140130412331311390.

Barcus H, Borchardt A, Dix M, Heurich C, McGrath J, McLeod-Henning D, Ropero-Miller J, Satcher R, Shute R, Witsil A. *Innovation in Forensics: A Community Effort*. Washington, DC. 2020. National Institute of Justice (NIJ). https://forensiccoe.org/private/65481656d71b3

Barrio PA, Crespillo M, Luque JA, Aler M, Baeza-Richer C, Baldassarri L, Carnevali E, Coufalova P, Flores I, Garcia O, Garcia MA, Gonzalez R, Hernandez A, Ingles V, Luque GM, Mosquera-Miguel A, Pedrosa S, Pontes ML, Porto MJ, Posada Y, Ramella MI, Ribeiro T, Riego E, Sala A, Saragoni VG, Serrano A, Vannelli S. GHEP-ISFG Collaborative Exercise on Mixture Profiles (GHEP-MIX06). Reporting Conclusions: Results and Evaluation. *Forensic Science International: Genetics*. 2018; 35:156-163. doi:10.1016/j.fsigen.2018.05.005.

Barshi I, Healy AF. Checklist Procedures and the Cost of Automaticity. *Memory and Cognition*. 1993; 21(4):496-505. doi:10.3758/bf03197181.

Basset P, Blandin P, Grini A, Delemont S, Samie L, Castella V. A Simplified Protocol for the Detection of Blood, Saliva, and Semen from a Single Biological Trace Using Immunochromatographic Tests. *Forensic Science, Medicine and Pathology*. 2022; 18(2):141-8. doi:10.1007/s12024-021-00453-2.

Bauer DW, Butt N, Hornyak JM, Perlin MW. Validating TrueAllele® Interpretation of DNA Mixtures Containing up to Ten Unknown Contributors. *Journal of Forensic Sciences*. 2020; 65(2):380-98. doi:10.1111/1556-4029.14204.

Becker WS, Dale WM, Pavur EJ. Forensic Science in Transition: Critical Leadership Challenges. *Forensic Science Policy & Management: An International Journal*. 2010; 1(4):214-23. doi:10.1080/19409044.2010.508507.

Benschop CCG, Connolly E, Ansell R, Kokshoorn B. Results of an Inter and Intra Laboratory Exercise on the Assessment of Complex Autosomal DNA Profiles. *Science & Justice*. 2017; 57(1):21-7. doi:10.1016/j.scijus.2016.10.001.

Benschop CCG, Hoogenboom J, Hovers P, Slagter M, Kruise D, Parag R, Steensma K, Slooten K, Nagel JHA, Dieltjes P, van Marion V, van Paassen H, de Jong J, Creeten C, Sijen T, Kneppers ALJ. DNAxs/DNAStatistX: Development and Validation of a Software Suite for the Data Management and Probabilistic Interpretation of DNA Profiles. *Forensic Science International: Genetics*. 2019; 42:81-9. doi:10.1016/j.fsigen.2019.06.015.

Benschop CCG, van der Linden J, Hoogenboom J, Ypma R, Haned H. Automated Estimation of the Number of Contributors in Autosomal Short Tandem Repeat Profiles Using a Machine Learning Approach. *Forensic Science International: Genetics*. 2019; 43:102150. doi:10.1016/j.fsigen.2019.102150.

Bieber FR, Buckleton J, Budowle B, Butler JM, Coble MD. Evaluation of Forensic DNA Mixture Evidence: Protocol for Evaluation, Interpretation, and Statistical Calculations Using the Combined Probability of Inclusion. *BMC Genetics*. 2016; 17(1):125. doi:10.1186/s12863-016-0429-7.

Biedermann A. The Strange Persistence of (Source) "Identification" Claims in Forensic Literature through Descriptivism, Diagnosticism and Machinism. *Forensic Science International: Synergy*. 2022; 4:100222. doi:doi:10.1016/j.fsisyn.2022.100222.

Biedermann A, Bozza S, Taroni F. Decision Theoretic Properties of Forensic Identification: Underlying Logic and Argumentative Implications. *Forensic Science International*. 2008; 177(2-3):120-32. doi:10.1016/j.forsciint.2007.11.008.

Biedermann A, Bozza S, Taroni F. The Decisionalization of Individualization. *Forensic Science International*. 2016; 266:29-38. doi:10.1016/j.forsciint.2016.04.029.

Biedermann A, Hicks T, Voisard R, Taroni F, Champod C, Aitken C, Evett IW. E-Learning Initiatives in Forensic Interpretation: Report on Experiences from Current Projects and Outlook. *Forensic Science International*. 2013; 230(1-3):2-7. doi:10.1016/j.forsciint.2012.10.011.

Biedermann A, Taroni F. Bayesian Networks for Evaluating Forensic DNA Profiling Evidence: A Review and Guide to Literature. *Forensic Science International: Genetics*. 2011; 6(2):147-57. doi:10.1016/j.fsigen.2011.06.009.

Bille T, Bright JA, Buckleton J. Application of Random Match Probability Calculations to Mixed STR Profiles. *Journal of Forensic Sciences*. 2013; 58(2):474-85. doi:10.1111/1556-4029.12067.

Bird C, Nagappan N, Murphy B, Gall H, Devanbu P. Don't Touch My Code!: Examining the Effects of Ownership on Software Quality. Presented at: Proceedings of the 19th ACM SIGSOFT Symposium and the 13th European Conference on Foundations of Software Engineering; 2011; Szeged, Hungary.

Blair JP, Rossmo DK. Evidence in Context: Bayes' Theorem and Investigations. *Police Quarterly*. 2010; 13(2):123-35. doi:10.1177/1098611110365686.

Borsuk LA, Vallone PM, Gettings KB. STRSeq: FAQ for Submitting. *Forensic Science International: Genetics Supplement Series*. 2022; 8:245-7.

Bregu J, Conklin D, Coronado E, Terrill M, Cotton RW, Grgicak CM. Analytical Thresholds and Sensitivity: Establishing RFU Thresholds for Forensic DNA Analysis. *Journal of Forensic Sciences*. 2013; 58(1):120-9. doi:10.1111/1556-4029.12008.

Bright DA, Goodman-Delahunty J. Gruesome Evidence and Emotion: Anger, Blame, and Jury Decision-Making. *Law and Human Behavior*. 2006; 30(2):183-202. doi:10.1007/s10979-006-9027-y.

Bright JA, Cheng K, Kerr Z, McGovern C, Kelly H, Moretti TR, Smith MA, Bieber FR, Budowle B, Coble MD, Alghafri R, Allen PS, Barber A, Beamer V, Buettner C, Russell M, Gehrig C, Hicks T, Charak J, Cheong-Wing K, Ciecko A, Davis CT, Donley M, Pedersen N, Gartside B, Granger D, Greer-Ritzheimer M, Reisinger E, Kennedy J, Grammer E, Kaplan M, Hansen D, Larsen HJ, Laureano A, Li C, Lien E, Lindberg E, Kelly C, Mallinder B, Malsom S, Yacovone-Margetts A, McWhorter A, Prajapati SM, Powell T, Shutler G, Stevenson K, Stonehouse AR, Smith L, Murakami J, Halsing E, Wright D, Clark L, Taylor DA, Buckleton J. STRmix™ Collaborative Exercise on DNA Mixture Interpretation. *Forensic Science International: Genetics*. 2019; 40:1-8. doi:10.1016/j.fsigen.2019.01.006.

Bright JA, Coble M. *Forensic DNA Profiling: A Practical Guide to Assigning Likelihood Ratios*. CRC Press: Boca Raton, Florida, 2019. doi:10.4324/9780429001017.

Bright JA, Jones Dukes M, Pugh S, Evett I, Buckleton J. Applying Calibration to LRs Produced by a DNA Interpretation Software. *Australian Journal of Forensic Sciences*. 2021; 53(2):147-53. doi:doi: 10.1080/00450618.2019.1682668.

Bright JA, Stevenson KE, Curran JM, Buckleton J. The Variability in Likelihood Ratios Due to Different Mechanisms. *Forensic Science International: Genetics*. 2015; 14:187-90. doi:10.1016/j.fsigen.2014.10.013.

Bright JA, Taylor D, Curran JM, Buckleton J. Developing Allelic and Stutter Peak Height Models for a Continuous Method of DNA Interpretation. *Forensic Science International: Genetics*. 2013; 7(2):296-304. doi:10.1016/j.fsigen.2012.11.013.

Bright JA, Taylor D, McGovern C, Cooper S, Russell L, Abarno D, Buckleton J. Developmental Validation of STRmix™, Expert Software for the Interpretation of Forensic DNA Profiles. *Forensic Science International: Genetics*. 2016; 23:226-39. doi:10.1016/j.fsigen.2016.05.007.

Brinkac LM, Richetelli N, Davoren JM, Bever RA, Hicklin RA. DNAmix 2021: Laboratory Policies, Procedures, and Casework Scenarios Summary and Dataset. *Data Brief*. 2023; 48:109150. doi:10.1016/j.dib.2023.109150.

Brookes C, Bright JA, Harbison S, Buckleton J. Characterising Stutter in Forensic STR Multiplexes. *Forensic Science International: Genetics*. 2012; 6(1):58-63. doi:10.1016/j.fsigen.2011.02.001.

Brooklyn Defender Services. The Kinship Problem. Accessed March 27, 2024. https://indefenseof.us/issues/kinship-problem.

Brooks DW. Chapter 6: Creating a Risk-Aware Culture. *Enterprise Risk Management*. Wiley Online Library: 2009:87-95. doi:10.1002/9781118267080.ch6.

Brown B. Reversion Therapy: Adult Coloring Books and Mental Health. Accessed March 26, 2024. https://www.gearhungry.com/adult-coloring-books-mental-health/.

Brumby DP, Cox AL, Back J, Gould SJ. Recovering from an Interruption: Investigating Speed-Accuracy Trade-Offs in Task Resumption Behavior. *Journal of Experimental Psychology: Applied*. 2013; 19(2):95-107. doi:10.1037/a0032696.

Buckleton J, Bright JA, Cheng K, Budowle B, Coble MD. NIST Interlaboratory Studies Involving DNA Mixtures (MIX13): A Modern Analysis. *Forensic Science International: Genetics*. 2018; 37:172-179. doi:10.1016/j.fsigen.2018.08.014.

Buckleton J, Bright JA, Gittelson S, Moretti TR, Onorato AJ, Bieber FR, Budowle B, Taylor DA. The Probabilistic Genotyping Software STRmix: Utility and Evidence for Its Validity. *Journal of Forensic Sciences*. 2019; 64(2):393-405. doi:10.1111/1556-4029.13898.

Buckleton J, Bright JA, Taylor D. *Forensic DNA Evidence Interpretation*. 2nd ed. CRC Press: Boca Raton, 2016. doi:10.4324/9781315371115.

Buckleton J, Bright JA, Taylor D, Evett I, Hicks T, Jackson G, Curran JM. Helping Formulate Propositions in Forensic DNA Analysis. *Science & Justice*. 2014; 54(4):258-61. doi:10.1016/j.scijus.2014.02.007.

Buckleton J, Curran J. A Discussion of the Merits of Random Man Not Excluded and Likelihood Ratios. *Forensic Science International: Genetics*. 2008; 2(4):343-8. doi:10.1016/j.fsigen.2008.05.005.

Buckleton J, Taylor D, Bright JA, Hicks T, Curran JM. When Evaluating DNA Evidence within a Likelihood Ratio Framework, Should the Propositions Be Exhaustive? *Forensic Science International: Genetics*. 2021; 50:102406. doi:10.1016/j.fsigen.2020.102406.

Budowle B, Onorato AJ, Callaghan TF, Della Manna A, Gross AM, Guerrieri RA, Luttman JC, McClure DL. Mixture Interpretation: Defining the Relevant Features for Guidelines for the Assessment of Mixed DNA Profiles in Forensic Casework. *Journal of Forensic Sciences*. 2009; 54(4):810-21. doi:10.1111/j.1556-4029.2009.01046.x.

Budowle B, Sajantila A. Revisiting Informed Consent in Forensic Genomics in Light of Current Technologies and the Times. *International Journal of Legal Medicine*. 2023; 137(2):551-65. doi:10.1007/s00414-023-02947-w.

Buel E, LaFountain M, Schwartz M, Walkinshaw M. Evaluation of Capillary Electrophoresis Performance Through Resolution Measurements. *Journal of Forensic Sciences*. 2001; 46(2):341-5. doi:10.1520/jfs14968j.

Bull R, Blandón-Gitlin I. *The Routledge International Handbook of Legal and Investigative Psychology*. Routledge: London, UK, 2019. doi:10.4324/9780429326530.

Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF). Firearms-Related Training for Law Enforcement. ATF. Accessed March 26, 2024. https://www.atf.gov/careers/firearms-related-training-law-enforcement.

Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF). Laboratory Services Quality Documents. Accessed March 26, 2024. https://www.atf.gov/file/164071/download.

Bureau of Justice Assistance. Paul Coverdell Forensic Science Improvement Grants Program. Accessed March 26, 2024. https://bja.ojp.gov/program/coverdell/overview.

Bureau of Justice Assistance. Training & Technical Assistance. Accessed March 26, 2024. https://bja.ojp.gov/training-technical-assistance.

Burmuzoska I, Hogg K, Raymond J, Hitchcock C, Meakin GE. Comparison of Operational DNA Recovery Methods: Swabs Versus Tapelifts. *Forensic Science International: Genetics Supplement Series*. 2022; 8:50-2. doi:10.1016/j.fsigss.2022.09.019.

Busey T, Klutzke M. Calibrating the Perceived Strength of Evidence of Forensic Testimony Statements. *Science & Justice*. 2023; 63(1):38-53. doi:10.1016/j.scijus.2022.10.003.

Butler ER, Yang H, Perez T, Almubarak I, Zapata J, Bakshi H, Sutherland M, Siegel D. The Development and Validation of a Multiple Reaction Monitoring (MRM) Mass Spectrometry (MS) Assay for Confident Identification of Protein Biomarkers for Blood, Semen, and Saliva. 73rd AAFS Annual Scientific Meeting, Virtual American Academy of Forensic Sciences, 2021. https://www.aafs.org/sites/default/files/media/documents/AAFS-2021-B6.pdf

Butler JM. *Advanced Topics in Forensic DNA Typing: Interpretation*. Elsevier Academic Press: San Diego, CA, 2014.

Butler JM. *Advanced Topics in Forensic DNA Typing: Methodology*. Elsevier Academic Press: San Diego, CA, 2011.

Butler JM. *Debunking Some Urban Legends Surrounding Validation Within the Forensic DNA Community*. Gaithersburg, Maryland, USA. 2006. National Institute of Standards and Technology (NIST). https://projects.nfstc.org/workshops/resources/literature/debunking%20validation%20butler.pdf.

Butler JM. *Fundamentals of Forensic DNA Typing*. Elsevier Academic Press: San Diego, CA, 2009. doi:10.1016/C2009-0-01945-X.

Butler JM. Recent Advances in Forensic Biology and Forensic DNA Typing: INTERPOL Review 2019-2022. *Forensic Science International: Synergy*. 2023; 6:100311. doi:10.1016/j.fsisyn.2022.100311.

Butler JM, Buel E, Crivellente F, McCord BR. Forensic DNA Typing by Capillary Electrophoresis Using the ABI Prism 310 and 3100 Genetic Analyzers for STR Analysis. *Electrophoresis*. 2004; 25(10-11):1397-412. doi:10.1002/elps.200305822.

Butler JM, Cotton RW, Prinz M, Word C. MVPs of Forensic DNA: Examining the Most Valuable Publications in the Field. 2021 AAFS Virtual Meeting, Virtual American Academy of Forensic Sciences, 2021. https://strbase.nist.gov/NIST_Resources/Presentations/2021/AAFS2021-W19-Handouts.pdf

Butler JM, Iyer H, Press R, Taylor MK, Vallone PM, Willis S. *DNA Mixture Interpretation: A NIST Scientific Foundation Review. NISTIR 8351-Draft.* 2021. doi: doi:10.6028/NIST.IR.8351-draft.

Butler JM, Kline MC. NIST Mixture Interpretation Interlaboratory Study 2005 (MIX05). Presented at: Promega 16th International Symposium on Human Identification 2005; Grapevine, TX. https://strbase-archive.nist.gov/interlab/MIX05/MIX05poster.pdf

Butler JM, Kline MC, Coble MD. NIST Interlaboratory Studies Involving DNA Mixtures (MIX05 and MIX13): Variation Observed and Lessons Learned. *Forensic Science International: Genetics*. 2018; 37:81-94. doi:10.1016/j.fsigen.2018.07.024.

Butler JM, Willis S. Interpol Review of Forensic Biology and Forensic DNA Typing 2016-2019. *Forensic Science International: Synergy*. 2020; 2:352-67. doi:10.1016/j.fsisyn.2019.12.002.

Cadola L, Charest M, Lavallée C, Crispino F. The Occurrence and Genesis of Transfer Traces in Forensic Science: A Structured Knowledge Database. *Canadian Society of Forensic Science Journal*. 2021; 54(2):86-100. doi:10.1080/00085030.2021.1890941.

Camilleri A, Abarno D, Bird C, Coxon A, Mitchell N, Redman K, Sly N, Wills S, Silenieks E, Simpson E, Lindsay H. A Risk-Based Approach to Cognitive Bias in Forensic Science. *Science & Justice*. 2019; 59(5):533-43. doi:10.1016/j.scijus.2019.04.003.

Carracedo A, Beckmann A, Bengs A, Brinkmann B, Caglia A, Capelli C, Gill P, Gusmao L, Hagelberg C, Hohoff C, Hoste B, Kihlgren A, Kloosterman A, Myhre Dupuy B, Morling N, O'Donnell G, Parson W, Phillips C, Pouwels M, Scheithauer R, Schmitter H, Schneider PM, Schumm J, Skitsa I, Stradmann-Bellinghausen B, Stuart M, Syndercombe Court D, Vide C. Results of a Collaborative Study of the EDNAP Group Regarding the Reproducibility and Robustness of the Y-Chromosome STRs DYS19, DYS389 I and II, DYS390 and DYS393 in a PCR Pentaplex Format. *Forensic Science International*. 2001; 119(1):28-41. doi:10.1016/s0379-0738(00)00395-9.

Catoggio D, Bunford J, Taylor D, Wevers G, Ballantyne KN, Morgan R. An Introductory Guide to Evaluative Reporting in Forensic Science. *Australian Journal of Forensic Sciences*. 2019; 51(sup1):S247-51. doi:10.1080/00450618.2019.1568560.

Cavanagh RR, Berge A, Coute A, Fazio R, Graham T, Marshall C, Miller J, Mullen L, Sozer A, Word C. Notes from the NIST Research Innovation to Implementation in Forensic Science Symposium (RI2I). NIST Special Publication (SP) 2100-02. 2019. doi:10.6028/nist.Sp.2100-02

Center for Open Science. Open Science Frammework (Osf) Home. Accessed March 27, 2024. https://osf.io/.

Center for Open Science. Registered Reports: Peer Review before Results Are Known to Align Scientific Values and Practices. Accessed March 26, 2024. https://www.cos.io/initiatives/registered-reports.

Center for Statistics and Applications in Forensic Science (CSAFE). Online Courses. Accessed January 15, 2024. https://learn.forensicstats.org/.

Centers for Disease Control and Prevention. Preferred Terms for Select Population Groups & Communities. Accessed March 26, 2024. https://www.cdc.gov/healthcommunication/Preferred_Terms.html.

Chaitanya L, Walsh S, Andersen JD, Ansell R, Ballantyne KN, Ballard D, Banemann R, Bauer CM, Bento AM, Brisighelli F, Capal T, Clarisse L, Gross TE, Haas C, Hoff-Olsen P, Hollard C, Keyser C, Kiesler KM, Kohler P, Kupiec T, Linacre A, Minawi A, Morling N, Nilsson H, Noren L, Ottens R, Palo JU, Parson W, Pascali VL, Phillips C, Porto MJ, Sajantila A, Schneider PM, Sijen T, Sochtig J, Syndercombe-Court D, Tillmar A, Turanska M, Vallone PM, Zatkalikova L, Zidkova A, Branicki W, Kayser M. Collaborative EDNAP Exercise on the IrisPlex System for DNA-Based Prediction of Human Eye Colour. *Forensic Science International: Genetics*. 2014; 11:241-51. doi:10.1016/j.fsigen.2014.04.006.

Chapman W, Hicklin RA, Taylor M. *Beginners Guide to Biometric and Forensic Science Human Subjects Research Protections. NIST Special Publication (Sp) 1289*. National Institute of Standards and Technology,. 2023. doi: 10.6028/NIST.SP.1289. https://nvlpubs.nist.gov/nistpubs/SpecialPublications/NIST.SP.1289.pdf.

Chin JM, McFadden R, Edmond G. Forensic Science Needs Registered Reports. *Forensic Science International: Synergy*. 2020; 2:41-5. doi:10.1016/j.fsisyn.2019.10.005.

Chin JM, Ribeiro G, Rairden A. Open Forensic Science. *Journal of Law and the Biosciences*. 2019; 6(1):255-88. doi:10.1093/jlb/lsz009.

Christensen AM, Crowder CM, Ousley SD, Houck MM. Error and Its Meaning in Forensic Science. *Journal of Forensic Sciences*. 2014; 59(1):123-6. doi:10.1111/1556-4029.12275.

Chu S. Duty to Correct and Notify. In: Houck MM, ed. *Encyclopedia of Forensic Sciences*. 3rd ed. Elsevier: Oxford, 2023:186-92. doi:10.1016/B978-0-12-823677-2.00172-0.

Coble MD, Bright JA. Probabilistic Genotyping Software: An Overview. *Forensic Science International: Genetics*. 2019; 38:219-24. doi:10.1016/j.fsigen.2018.11.009.

Coble MD, Buckleton J, Butler JM, Egeland T, Fimmers R, Gill P, Gusmao L, Guttman B, Krawczak M, Morling N, Parson W, Pinto N, Schneider PM, Sherry ST, Willuweit S, Prinz M. DNA Commission of the International Society for Forensic Genetics: Recommendations on the Validation of Software Programs Performing Biostatistical Calculations for Forensic Genetics Applications. *Forensic Science International: Genetics*. 2016; 25:191-7. doi:10.1016/j.fsigen.2016.09.002.

Cold Spring Harbor Laboratory. bioRxiv: The Preprint Server for Biology. Accessed March 26, 2024. https://www.biorxiv.org/.

Cole SA. Forensics without Uniqueness, Conclusions without Individualization: The New Epistemology of Forensic Identification. *Law, Probability and Risk*. 2009; 8(3):233-55. doi:10.1093/lpr/mgp016.

Cole SA, Dioso-Villa R. Investigating the 'CSI Effect' Effect: Media and Litigation Crisis in Criminal Law. *Stanford Law Review*. 2008; 61:1335. doi:ssrn.com/abstract=1401417.

Coles-Brennan C, Sulley A, Young G. Management of Digital Eye Strain. *Clinical and Experimental Optometry*. 2019; 102(1):18-29. doi:10.1111/cxo.12798.

Collins J. *HR Management in the Forensic Science Laboratory: A 21st Century Approach to Effective Crime Lab Leadership*. Waltham: Academic Press: 2018. doi:10.106/C2013-0-19010-1.

Colorado Bureau of Investigation Forensic Services. *Quality Incident Review* 2024. *QP 11 ISO 710, Revision 5: 3/21/2024*. https://cbifs.qualtraxcloud.com/ShowDocument.aspx?ID=6959.

Colvin J, Tobler N, Anderson JA. Productivity and Multi-Screen Computer Displays. *Rocky Mountain Communication Review*. 2004;2(1). https://workolyk.com/wp-content/uploads/2015/07/utahdisplaystudy.pdf

Commission Internationale de l'Eclairage (CIE). *Method of Measuring and Specifying Colour Rendering Properties of Light Sources*. Vol. 13.3. Vienna. 1995. doi: doi.org/10.1002/col.5080200313. https://cie.co.at/publications/method-measuring-and-specifying-colour-rendering-properties-light-sources

Committee on Recommendations for Quality and Quantity of Illumination of the IES (RQQ). Selection of Illuminance Values for Interior Lighting Design. *Journal of the Illuminating Engineering Society*. 1980; 9(3):188-90. doi:10.1080/00994480.1980.10747897.

Community Oriented Policing Services. *Law Enforcement Mental Health and Wellness Act: Report to Congress*. 2019. https://cops.usdoj.gov/pdf/2019AwardDocs/lemhwa/Report_to_Congress.pdf.

Cook R, Evett IW, Jackson G, Jones PJ, Lambert JA. A Hierarchy of Propositions: Deciding Which Level to Address in Casework. *Science & Justice*. 1998; 38(4):231-9. doi:10.1016/S1355-0306(98)72117-3.

Cook R, Evett IW, Jackson G, Jones PJ, Lambert JA. A Model for Case Assessment and Interpretation. *Science & Justice*. 1998; 38(3):151-6. doi:10.1016/S1355-0306(98)72099-4.

Cooper GS, Meterko V. Cognitive Bias Research in Forensic Science: A Systematic Review. *Forensic Science International*. 2019; 297:35-46. doi:10.1016/j.forsciint.2019.01.016.

Cornell Law School Legal Information Institute. 29 CFR § 1635.8 - Acquisition of Genetic Information. Cornell Law. Updated December 20 2018. Accessed March 26, 2024. https://www.law.cornell.edu/cfr/text/29/1635.8.

Cornell Law School Legal Information Institute. Federal Rule 16. Discovery and Inspection. 2021. https://www.law.cornell.edu/rules/frcrmp/rule_16

Cornell Law School Legal Information Institute. Frye Standard. Updated December 2022. Accessed March 26, 2024. https://www.law.cornell.edu/wex/frye_standard.

Council for International Organizations of Medical Sciences. *International Ethical Guidelines for Biomedical Research Involving Human Participants*. 2016. doi: doi.org/10.56759/rgxl7405.

Council of Australian University Librarians. Open Research Toolkit. Accessed March 26, 2024. https://caul.libguides.com/open-research-toolkit/incentives.

County Court of St Lawrence, *The People of the State of New York v. Oral Nicholas Hillary*, (2016). https://www.northcountrypublicradio.org/assets/files/08-26-16DecisionandOrder-DNAAnalysisAdmissibility.pdf.

Coursera. Challenging Forensic Science: How Science Should Speak to Court. Accessed March 26, 2024. https://www.coursera.org/learn/challenging-forensic-science.

Cox LA. What's Wrong with Risk Matrices? *Risk Analysis*. 2008; 28(2):497-512. doi:10.1111/j.1539-6924.2008.01030.x.

Crespillo M, Barrio PA, Luque JA, Alves C, Aler M, Alessandrini F, Andrade L, Barretto RM, Bofarull A, Costa S, Garcia MA, Garcia O, Gaviria A, Gladys A, Gorostiza A, Hernandez A, Pinero MH, Hombreiro L, Ibarra AA, Jimenez MJ, Luque GM, Madero P, Martinez-Jarreta B, Masciovecchio MV, Modesti NM, Moreno F, Pagano S, Pedrosa S, Plaza G, Prat E, Puente J, Rendo F, Ribeiro T, Sala A, Santamaria E, Saragoni VG, Whittle MR. GHEP-ISFG Collaborative Exercise on Mixture Profiles of Autosomal STRs (GHEP-MIX01, GHEP-MIX02 and GHEP-MIX03): Results and Evaluation. *Forensic Science International: Genetics*. 2014; 10:64-72. doi:10.1016/j.fsigen.2014.01.009.

Curran JM, Buckleton J. Inclusion Probabilities and Dropout. *Journal of Forensic Sciences*. 2010; 55(5):1171-3. doi:10.1111/j.1556-4029.2010.01446.x.

Cybergenetics. Forensics: Products and Services. Accessed March 26, 2024. https://www.cybgen.com/.

Czerwinski M, Robertson G, Meyers B, Smith G, Robbins D, Tan D. Large Display Research Overview. *Extended Abstracts on Human Factors in Computing Systems*. 2006:69-74. doi:10.1145/1125451.1125471.

Damelio R. *The Basics of Process Mapping*. 2nd ed. CRC Press: New York, NY, 2011.

Darr ED, Argote L, Epple D. The Acquisition, Transfer, and Depreciation of Knowledge in Service Organizations: Productivity in Franchises. *Management Science*. 1995; 41(11):1750-62. doi:10.1287/mnsc.41.11.1750.

Davis DM, Hayes JA. What Are the Benefits of Mindfulness? A Practice Review of Psychotherapy-Related Research. *Psychotherapy*. 2011; 48(2):198-208. doi:10.1037/a0022062.

Davis MC, Leach DJ, Clegg CW. The Physical Environment of the Office: Contemporary and Emerging Issues. *International Review of Industrial and Organizational Psychology*. 2011; 26(1):193-255. doi:10.1002/9781119992592.ch6.

Dawley DD, Munyon TP. The Effects of Politics on Job Satisfaction in Crime Lab Employees. *Forensic Science Policy & Management: An International Journal*. 2012; 3(4):159-64. doi:10.1080/19409044.2013.826306.

De Croon EM, Sluiter JK, Kuijer PP, Frings-Dresen MH. The Effect of Office Concepts on Worker Health and Performance: A Systematic Review of the Literature. *Ergonomics*. 2005; 48(2):119-34. doi:10.1080/00140130512331319409.

de Keijser J, Elffers H. Understanding of Forensic Expert Reports by Judges, Defense Lawyers and Forensic Professionals. *Psychology, Crime & Law*. 2012; 18(2):191-207. doi:10.1080/10683161003736744.

de Looze MP, Vink P, Koningsveld EAP, Kuijt-Evers L, Van Rhijn G. Cost‐Effectiveness of Ergonomic Interventions in Production. *Human Factors and Ergonomics in Manufacturing & Service Industries*. 2010; 20(4):316-23. doi:10.1002/hfm.20223.

De Wolff TR, Kal AJ, Berger CEH, Kokshoorn B. A Probabilistic Approach to Body Fluid Typing Interpretation: An Exploratory Study on Forensic Saliva Testing. *Law, Probability and Risk*. 2015; 14(4):323–39. doi:10.1093/lpr/mgv014.

de Zoete J, Curran J, Sjerps M. A Probabilistic Approach for the Interpretation of RNA Profiles as Cell Type Evidence. *Forensic Science International: Genetics*. 2016; 20:30-44. doi:10.1016/j.fsigen.2015.09.007.

de Zoete J, Oosterman W, Kokshoorn B, Sjerps M. Cell Type Determination and Association with the DNA Donor. *Forensic Science International: Genetics*. 2016; 25:97-111. doi:10.1016/j.fsigen.2016.08.004.

Degani A, Wiener EL. *Human Factors of Flight-Deck Checklists: The Normal Checklist*. NASA Contractor Report 177549. 1990:1-71. https://ntrs.nasa.gov/api/citations/19910017830/downloads/19910017830.pdf.

Denison SJ, Lopes EM, D'Costa L, Newman JC. Positive Prostate-Specific Antigen (PSA) Results in Semen-Free Samples. *Canadian Society of Forensic Science Journal*. 2004; 37(4):197-206. doi:10.1080/00085030.2004.10757576.

Denzau AT, Minassians HP, Roy RK. Learning to Cooperate: Applying Deming's New Economics and Denzau and North's New Institutional Economics to Improve Interorganizational Systems Thinking. *Kyklos*. 2016; 69(3):471-91. doi:10.1111/kykl.12117.

DiFrancesco J, Sutton J. Re-Evaluation of the Seratec® PSA Semiquant Test: Comparison of Kit Provided Buffer with Phosphate Buffer Saline. *Canadian Society of Forensic Science Journal*. 2015; 48(3):137-51. doi:10.1080/00085030.2015.1051315.

Dismukes K, Nowinski J. Chapter 16: Prospective Memory, Concurrent Task Management and Pilot Error. *Attention: From Theory to Practice*. Oxford University Press: New York, NY, 2006:225-36.

District of Columbia Court of Appeals. *Frye v. United States 293 F. 1013*. 1923.

DNA-TrAC. Keeping Track of DNA Transfer. Accessed Feb 10, 2024. https://www.dropbox.com/sh/jf286hcollyerlf/AABQHfhGGiB03YdcJgpO4NUga?+dl=0.

Dror IE. Cognitive and Human Factors in Expert Decision Making: Six Fallacies and the Eight Sources of Bias. *Analytical Chemistry*. 2020; 92(12):7998-8004. doi:10.1021/acs.analchem.0c00704.

Dror IE. Cognitive Forensics and Experimental Research About Bias in Forensic Casework. *Science & Justice*. 2012; 52(2):128-30. doi:10.1016/j.scijus.2012.03.006.

Dror IE. Commentary On: The Error in "Error Rate": Why Error Rates Are So Needed, Yet So Elusive. *Journal of Forensic Sciences*. 2020; 65(4):1034-9. doi:10.1111/1556-4029.14435.

Dror IE, Hampikian G. Subjectivity and Bias in Forensic DNA Mixture Interpretation. *Science & Justice*. 2011; 51(4):204-8. doi:10.1016/j.scijus.2011.08.004.

Dror IE, Kukucka J. Linear Sequential Unmasking-Expanded (LSU-E): A General Approach for Improving Decision Making as Well as Minimizing Noise and Bias. *Forensic Science International: Synergy*. 2021; 3:100161. doi:10.1016/j.fsisyn.2021.100161.

Dror IE, Langenburg G. "Cannot Decide": The Fine Line Between Appropriate Inconclusive Determinations Versus Unjustifiably Deciding Not to Decide. *Journal of Forensic Sciences*. 2019; 64(1):10-5. doi:10.1111/1556-4029.13854.

Dror IE, Péron AE, Hind S-L, Charlton D. When Emotions Get the Better of Us: The Effect of Contextual Top-Down Processing on Matching Fingerprints. *Applied Cognitive Psychology*. 2005; 19(6):799-809. doi:10.1002/acp.1130.

Dror IE, Pierce ML. ISO Standards Addressing Issues of Bias and Impartiality in Forensic Work. *Journal of Forensic Sciences*. 2020; 65(3):800-8. doi:10.1111/1556-4029.14265.

Dror IE, Thompson WC, Meissner CA, Kornfield I, Krane D, Saks MJ, Risinger M. Letter to the Editor- Context Management Toolbox: A Linear Sequential Unmasking (LSU) Approach for Minimizing Cognitive Bias in Forensic Decision Making. *Journal of Forensic Sciences*. 2015; 60(4):1111-2. doi:10.1111/1556-4029.12805.

Duffy KR, Gurram N, Peters KC, Wellner G, Grgicak CM. Exploring STR Signal in the Single- and Multicopy Number Regimes: Deductions from an in Silico Model of the Entire DNA Laboratory Process. *Electrophoresis*. 2017; 38(6):855-68. doi:10.1002/elps.201600385.

Duffy KR, Lun DS, Mulcahy MM, O'Donnell L, Sheth N, Grgicak CM. Evidentiary Evaluation of Single Cells Renders Highly Informative Forensic Comparisons across Multifarious

Admixtures. *Forensic Science International: Genetics*. 2023; 64:102852. doi:10.1016/j.fsigen.2023.102852.

Duke K, Myers S, Cuenca D, Wallin J. Improving the Utilization of STRmix™ Variance Parameters as Semi-Quantitative Profile Modeling Metrics. *Genes (Basel)*. 2022; 14(1):102. doi:10.3390/genes14010102.

Durose MR, Walsh KA, Burch AM. *Census of Publicly Funded Forensic Crime Laboratories, 2009*. United States Department of Justice. 2009. https://bjs.ojp.gov/content/pub/pdf/cpffcl09.pdf.

Eastwood J, Caldwell J. Educating Jurors About Forensic Evidence: Using an Expert Witness and Judicial Instructions to Mitigate the Impact of Invalid Forensic Science Testimony. *Journal of Forensic Sciences*. 2015; 60(6):1523-8. doi:10.1111/1556-4029.12832.

Edmond G, Towler A, Growns B, Ribeiro G, Found B, White D, Ballantyne KN, Searston RA, Thompson MB, Tangen JM, Kemp RI, Martire K. Thinking Forensics: Cognitive Science for Forensic Practitioners. *Science & Justice*. 2017; 57(2):144-154. doi:10.1016/j.scijus.2016.11.005.

Edson MC. A Complex Adaptive Systems View of Resilience in a Project Team. *Systems Research and Behavioral Science*. 2012; 29(5):499-516. doi:10.1002/sres.2153.

Elaad E. Tunnel Vision and Confirmation Bias among Police Investigators and Laypeople in Hypothetical Criminal Contexts. *SAGE Open*. 2022; 12(2):1-10. doi:10.1177/:21582440221095022.

Eldridge H. Juror Comprehension of Forensic Expert Testimony: A Literature Review and Gap Analysis. *Forensic Science International: Synergy*. 2019; 1:24-34. doi:10.1016/j.fsisyn.2019.03.001.

Ellinas C, Allan N, Johansson A. Dynamics of Organizational Culture: Individual Beliefs Vs. Social Conformity. *PloS One*. 2017; 12(6):e0180193. doi:10.1371/journal.pone.0180193.

Elster N. How Forensic DNA Evidence Can Lead to Wrongful Convictions. *JSTOR Daily*. 2017. Accessed March 27, 2024. https://daily.jstor.org/forensic-dna-evidence-can-lead-wrongful-convictions/

Engineering ToolBox. Illuminance – Recommended Light Levels. Accessed March 27, 2024. https://www.engineeringtoolbox.com/light-level-rooms-d_708.html.

Ensenberger MG, Lenz KA, Matthies LK, Hadinoto GM, Schienman JE, Przech AJ, Morganti MW, Renstrom DT, Baker VM, Gawrys KM, Hoogendoorn M, Steffen CR, Martin P, Alonso A, Olson HR, Sprecher CJ, Storts DR. Developmental Validation of the PowerPlex® Fusion 6C System. *Forensic Science International: Genetics*. 2016; 21:134-44. doi:10.1016/j.fsigen.2015.12.011.

Ericsson K, Charness, N., Feltovich, P., & Hoffman, R. *The Cambridge Handbook of Expertise and Expert Performance*. Cambridge University Press: New York, NY, 2006. doi:10.1017/CBO9780511816796.

Ericsson KA, Lehmann AC. Expert and Exceptional Performance: Evidence of Maximal Adaptation to Task Constraints. *Annual Review of Psychology*. 1996; 47:273-305. doi:10.1146/annurev.psych.47.1.273.

Errickson D, Fawcett H, Thompson TJU, Campbell A. The Effect of Different Imaging Techniques for the Visualisation of Evidence in Court on Jury Comprehension. *International Journal of Legal Medicine*. 2020; 134(4):1451-5. doi:10.1007/s00414-019-02221-y.

EuroForMix. About. Accessed March 27, 2024. http://euroformix.com/.

European Network of Forensic Science Institutes (ENFSI). *Best Practice Manual for Human Forensic Biology and DNA Profiling ENFSI-DNA-Bpm-03, Version 01*. 2022. https://enfsi.eu/wp-content/uploads/2022/12/ENFSI-DNA-BPM-03.pdf.

European Network of Forensic Science Institutes (ENFSI). *ENFSI Guideline for Evaluative Reporting in Forensic Science: Strengthening the Evaluation of Forensic Results across Europe (STEOFRAE), Version 3.0*. 2015. https://enfsi.eu/wp-content/uploads/2016/09/m1_guideline.pdf.

European Network of Forensic Science Institutes (ENFSI). *Guideline for DNA Contamination Minimization in DNA Laboratories*. 2023. https://enfsi.eu/wp-content/uploads/2023/10/ENFSI-GUIDELINE-FOR-DNA-CONTAMINATION-MINIMIZATION-IN-DNA-LABORATORIES.pdf.

European Network of Forensic Science Institutes (ENFSI). *Guideline for the Training of Staff in Forensic DNA-Laboratories*. 2022. https://enfsi.eu/wp-content/uploads/2022/03/Guideline-for-the-Training-of-DNA-Staff.pdf.

European Network of Forensic Science Institutes (ENFSI). *Guidelines for the Single Laboratory Validation of Instrumental and Human Based Methods in Forensic Science, Version 2.0*. 2014. https://enfsi.eu/wp-content/uploads/2017/06/Guidelines-for-the-single-laboratory-Validation-of-Instrumental-and-Human-Based-Methods-in-Forensic-Sciene_2014-version-2.0.pdf.

European Network of Forensic Science Institutes (ENFSI). *Recommended Minimum Criteria for the Validation of Various Aspects of the DNA Profiling Process*. 2010. https://enfsi.eu/wp-content/uploads/2016/09/minimum_validation_guidelines_in_dna_profiling_-_v2010_0.pdf.

Evett IW. Avoiding the Transposed Conditional. *Science & Justice*. 1995; 35(2):127-31. doi:10.1016/S1355-0306(95)72645-4.

Evett IW. Bayesian Inference and Forensic Science: Problems and Perspectives. *Journal of the Royal Statistical Society: Series D (The Statistician)*. 1987; 36(2-3):99-105. doi:10.2307/2348502.

Evett IW. Towards a Uniform Framework for Reporting Opinions in Forensic Science Casework. *Science & Justice*. 1998; 38(3):198-202. doi:10.1016/S1355-0306(98)72105-7.

Evett IW, Gill PD, Jackson G, Whitaker J, Champod C. Interpreting Small Quantities of DNA: The Hierarchy of Propositions and the Use of Bayesian Networks. *Journal of Forensic Sciences*. 2002; 47(3):520-30. doi:10.1520/jfs15291j.

Evett IW, Jackson G, Lambert JA. More on the Hierarchy of Propositions: Exploring the Distinction between Explanations and Propositions. *Science & Justice*. 2000; 40(1):3-10. doi:10.1016/S1355-0306(00)71926-5.

Evett IW, Jackson G, Lambert JA, McCrossan S. The Impact of the Principles of Evidence Interpretation on the Structure and Content of Statements. *Science & Justice*. 2000; 40(4):233-9. doi:10.1016/S1355-0306(00)71993-9.

Evett IW, Weir BS. *Interpreting DNA Evidence: Statistical Genetics for Forensic Scientists*. Sinauer Associates Inc,: Sunderland, MA, 1998.

Expert Working Group for Human Factors in Handwriting Examination. Forensic Handwriting Examination and Human Factors: Improving the Practice through a Systems Approach. NIST IR 8282r1. National Institute of Standards and Technology; 2021. doi:10.6028/NIST.IR.8282r1

Expert Working Group on Human Factors in Latent Print Analysis. Latent Print Examination and Human Factors: Improving the Practice through a Systems Approach. National Institute of Standards and Technology; 2012. doi:10.6028/NIST.IR.7842

FDA Group. A Basic Guide to Writing Effective Standard Operating Procedures (SOPs). Accessed March 27, 2024. https://www.thefdagroup.com/blog/a-basic-guide-to-writing-effective-standard-operating-procedures-sops.

Federal Bureau of Investigation (FBI). FBI Services: Training Academy. Accessed March 27, 2024. https://le.fbi.gov/training.

Federal Bureau of Investigation (FBI). Frequently Asked Questions on CODIS and NDIS. Accessed March 27, 2024. https://www.fbi.gov/how-we-can-help-you/dna-fingerprint-act-of-2005-expungement-policy/codis-and-ndis-fact-sheet.

Federal Bureau of Investigation (FBI). Law Enforcement Resources: CODIS-NDIS Statistics. Accessed March 27, 2024. https://le.fbi.gov/science-and-lab/biometrics-and-fingerprints/codis/codis-ndis-statistics.

Federal Bureau of Investigation (FBI). *Law Enforcement Resources: National DNA Index System (NDIS) Operational Procedures Manual, Version 12*. 2022. https://le.fbi.gov/file-repository/ndis-operational-procedures-manual-version-12-070123.pdf/view.

Federal Bureau of Investigation (FBI). *Quality Assurance Standards for Forensic DNA Testing Laboratories*. 2020. https://le.fbi.gov/file-repository/forensic-qas-070120.pdf/view.

Federal Bureau of Investigation (FBI) Laboratory. *National DNA Index System (NDIS) Operational Procedures Manual, Version 4*. 2016. https://ucr.fbi.gov/lab/biometric-analysis/codis/ndis-procedures-manual.

Federal Rule of Evidence. *FRE 702 Testimony by Expert Witnesses*. 2011. https://www.law.cornell.edu/rules/fre/rule_702.

Federal Rule of Evidence. *FRE 704 Opinion on an Ultimate Issue*. 2011. https://www.law.cornell.edu/rules/fre/rule_704.

Feigenson N, Eryn N, Jalbert M. Cognitive Fluency in the Courtroom. *The Routledge International Handbook of Legal and Investigative Psychology*. 2019:102-15. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3752317

Fenton N, Neil M, Hsu A. Calculating and Understanding the Value of Any Type of Match Evidence When There Are Potential Testing Errors. *Artificial Intelligence and Law*. 2013; 22(1):1-28. doi:10.1007/s10506-013-9147-x.

Findley KA, Scott MS. The Multiple Dimensions of Tunnel Vision in Criminal Cases. *Wisconsin Law Review*. 2006:291-397.

Finkelstein MO, Fairley WB. A Bayesian Approach to Identification Evidence. *Harvard Law Review*. 1970; 83(3):489-517. doi:10.2307/1339656.

Fischhoff B. Hindsight Not Equal to Foresight: The Effect of Outcome Knowledge on Judgment under Uncertainty. *Quality & Safety in Health Care*. 2003; 12(4):304-11. doi:10.1136/qhc.12.4.304.

Florida International University. Research Forensic Library. Accessed March 27, 2024. https://forensiclibrary.org/.

Florida International University. Science Serving Justice. Accessed March 27, 2024. https://gfjc.fiu.edu/.

Foreman LA, Evett IW. Statistical Analyses to Support Forensic Interpretation for a New Ten-Locus STR Profiling System. *International Journal of Legal Medicine*. 2001; 114(3):147-55. doi:10.1007/s004140000138.

Forensic Science Regulator. *Codes of Practice and Conduct: Development of Evaluative Opinions. FSR-C-118, Issue 1*. 2021. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/960051/FSR-C-118_Interpretation_Appendix_Issue_1__002_.pdf.

Forensic Science Regulator. *Guidance: Proficiency Testing Guidance for DNA Mixture Analysis and Interpretation. FSR-G-224, Issue 1*. 2020. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/894598/G224_DNA_Mix_PT_Guidelines__Issue1_2020.pdf.

Forensic Technology Center of Excellence (FTCoE). ASCLD Emerging Issues: Employee Wellness – Stress, Vicarious Trauma, and Resiliency for Forensic Science Professionals. Accessed March 27, 2024. https://forensiccoe.org/stress-vicarious-trauma-and-resiliency/.

Forensic Technology Center of Excellence (FTCoE). NIJ R&D Success Stories. National Institute of Justice, Office of Justice Programs, U.S. Department of Justice. Accessed March 27, 2024. https://forensiccoe.org/nij-success-stories/.

Forensic Technology Center of Excellence (FTCoE). *User Guide: Cost-Benefit Analysis Tool for Labor Expenditure Associated with Sexual Assault Kit Processing Workflows*. 2022. https://forensiccoe.org/private/6317b48de9b72.

Found B, Edmond G. Reporting on the Comparison and Interpretation of Pattern Evidence: Recommendations for Forensic Specialists. *Australian Journal of Forensic Sciences*. 2012; 44(2):193-6. doi:10.1080/00450618.2011.644260.

Found B, Ganas J. The Management of Domain Irrelevant Context Information in Forensic Handwriting Examination Casework. *Science & Justice*. 2013; 53(2):154-8. doi:10.1016/j.scijus.2012.10.004.

Found B, Rogers D. The Probative Character of Forensic Handwriting Examiners' Identification and Elimination Opinions on Questioned Signatures. *Forensic Science International*. 2008; 178(1):54-60. doi:10.1016/j.forsciint.2008.02.001.

Gallagher KM, Cameron L, De Carvalho D, Boule M. Does Using Multiple Computer Monitors for Office Tasks Affect User Experience? A Systematic Review. *Human Factors*. 2021; 63(3):433-49. doi:10.1177/0018720819889533.

Gamette MJ, Wickenheiser RA. Establishment of the National Technology Validation and Implementation Collaborative (NTVIC) and Forensic Investigative Genetic Genealogy Technology Validation Working Group (FIGG-TVWG). *Forensic Science International: Synergy*. 2023; 6:100317. doi:10.1016/j.fsisyn.2023.100317.

Garrett BL. *Autopsy of a Crime Lab: Exposing the Flaws in Forensics*. University of California Press: California, 2022. doi:10.2307/j.ctv1h9dkjv.

Garrett BL, Crozier WE, Grady R. Error Rates, Likelihood Ratios, and Jury Evaluation of Forensic Evidence. *Journal of Forensic Sciences*. 2020; 65(4):1199-1209. doi:10.1111/1556-4029.14323.

Gettings KB. Forensic DNA Open Dataset, National Institute of Standards and Technology. Accessed March 27, 2024. https://catalog.data.gov/dataset/forensic-dna-open-dataset-a26bc.

Gill P. DNA Evidence and Miscarriages of Justice. *Forensic Science International*. 2019; 294:e1-e3. doi:10.1016/j.forsciint.2018.12.003.

Gill P. How Misuse of DNA Evidence Has Led to Miscarriages of Justice. *The Justice Gap*. 2017. Accessed March 27, 2024. https://www.thejusticegap.com/misuse-dna-evidence-led-miscarriages-justice/

Gill P. Misleading DNA Evidence: Reasons for Miscarriages of Justice. *International Commentary on Evidence*. 2012; 10(1):55–71. doi:10.1515/ice-2014-0010.

Gill P, Benschop C, Buckleton J, Bleka O, Taylor D. A Review of Probabilistic Genotyping Systems: EuroForMix, DNAStatistX and STRMix™. *Genes (Basel)*. 2021; 12(10):1559. doi:10.3390/genes12101559.

Gill P, Haned H. A New Methodological Framework to Interpret Complex DNA Profiles Using Likelihood Ratios. *Forensic Science International: Genetics*. 2013; 7(2):251-63. doi:10.1016/j.fsigen.2012.11.002.

Gill P, Hicks T, Butler JM, Connolly E, Gusmao L, Kokshoorn B, Morling N, van Oorschot RAH, Parson W, Prinz M, Schneider PM, Sijen T, Taylor D. DNA Commission of the International Society for Forensic Genetics: Assessing the Value of Forensic Biological Evidence - Guidelines Highlighting the Importance of Propositions. Part II: Evaluation of Biological Traces Considering Activity Level Propositions. *Forensic Science International: Genetics*. 2020; 44:102186. doi:10.1016/j.fsigen.2019.102186.

Gill P, Hicks T, Butler JM, Connolly E, Gusmao L, Kokshoorn B, Morling N, van Oorschot RAH, Parson W, Prinz M, Schneider PM, Sijen T, Taylor D. DNA Commission of the International Society for Forensic Genetics: Assessing the Value of Forensic Biological Evidence - Guidelines Highlighting the Importance of Propositions: Part I: Evaluation of DNA Profiling Comparisons Given (Sub-) Source Propositions. *Forensic Science International: Genetics*. 2018; 36:189-202. doi:10.1016/j.fsigen.2018.07.003.

Gill P, Rowlands D, Tully G, Bastisch I, Staples T, Scott P. Manufacturer Contamination of Disposable Plastic-Ware and Other Reagents - an Agreed Position Statement by ENFSI, SWGDAM and BSAG. *Forensic Science International: Genetics*. 2010; 4(4):269-70. doi:10.1016/j.fsigen.2009.08.009.

Gittelson S, Kalafut T, Myers S, Taylor D, Hicks T, Taroni F, Evett IW, Bright JA, Buckleton J. A Practical Guide for the Formulation of Propositions in the Bayesian Approach to DNA Evidence Interpretation in an Adversarial Environment. *Journal of Forensic Sciences*. 2016; 61(1):186-95. doi:10.1111/1556-4029.12907.

Good IJ. *Probability and the Weighing of Evidence*. Charles Griffin & Company Limited: London, UK, 1950.

GoodTherapy. Critical Incident Stress Management. Accessed March 27, 2024. https://www.goodtherapy.org/learn-about-therapy/types/critical-incident-stress-management.

Gosch A, Courts C. On DNA Transfer: The Lack and Difficulty of Systematic Research and How to Do It Better. *Forensic Science International: Genetics*. 2019; 40:24-36. doi:10.1016/j.fsigen.2019.01.012.

GovInfo. *28 CFR 46 - Protection of Human Subjects*. 2022. https://www.govinfo.gov/app/details/CFR-2022-title28-vol2/CFR-2022-title28-vol2-part46/summary.

Grady C. Enduring and Emerging Challenges of Informed Consent. *The New England Journal of Medicine*. 2015; 372(9):855-62. doi:10.1056/NEJMra1411250.

Greiter BS, Renfro S, Carriquiry AL, Stern HS, Fabricant C, Meis M, Garcia L. The Scientific Literacy Project: A Collaborative Effort in Educating Legal Professionals on Forensic Evidence. 75th Annual American Academy of Forensic Sciences Symposium, Orlando, FL

2023. https://www.aafs.org/sites/default/files/media/documents/2023Proceedings_FINAL-june-1-23.pdf

Grgicak CM, Duffy KR, Lun DS. The a Posteriori Probability of the Number of Contributors When Conditioned on an Assumed Contributor. *Forensic Science International: Genetics*. 2021; 54:102563. doi:10.1016/j.fsigen.2021.102563.

Grgicak CM, Karkar S, Yearwood-Garcia X, Alfonse LE, Duffy KR, Lun DS. A Large-Scale Validation of NOCIt's a Posteriori Probability of the Number of Contributors and Its Integration into Forensic Interpretation Pipelines. *Forensic Science International: Genetics*. 2020; 47:102296. doi:10.1016/j.fsigen.2020.102296.

Grieser F, Pedell B. Exploring Risk Culture Controls: To What Extent Can the Development of Organizational Risk Culture Be Controlled and How? *Journal of Accounting & Organizational Change*. 2021; 18(5):752-88. doi:10.1108/jaoc-11-2020-0189.

Gross SR, Possley MJ, Roll KJ, Stephens KH. *Government Misconduct and Convicting the Innocent: The Role of Prosecutors, Police and Other Law Enforcement*. University of Michigan Law School. 2020. https://repository.law.umich.edu/cgi/viewcontent.cgi?article=1165&context=other.

Groysberg B, Lee J, Price J, Yo-Jud Cheng J. The Leader's Guide to Corporate Culture. *Harvard Business Review*. 2018. https://hbr.org/2018/01/the-leaders-guide-to-corporate-culture

Haapakangas A, Hongisto V, Eerola M, Kuusisto T. Distraction Distance and Perceived Disturbance by Noise - An Analysis of 21 Open-Plan Offices. *The Journal of the Acoustical Society of America*. 2017; 141(1):127-36. doi:10.1121/1.4973690.

Haas C, Hanson E, Anjos MJ, Ballantyne KN, Banemann R, Bhoelai B, Borges E, Carvalho M, Courts C, De Cock G, Drobnic K, Dotsch M, Fleming R, Franchi C, Gomes I, Hadzic G, Harbison SA, Harteveld J, Hjort B, Hollard C, Hoff-Olsen P, Huls C, Keyser C, Maronas O, McCallum N, Moore D, Morling N, Niederstatter H, Noel F, Parson W, Phillips C, Popielarz C, Roeder AD, Salvaderi L, Sauer E, Schneider PM, Shanthan G, Court DS, Turanska M, van Oorschot RA, Vennemann M, Vidaki A, Zatkalikova L, Ballantyne J. RNA/DNA Co-Analysis from Human Menstrual Blood and Vaginal Secretion Stains: Results of a Fourth and Fifth Collaborative EDNAP Exercise. *Forensic Science International: Genetics*. 2014; 8(1):203-12. doi:10.1016/j.fsigen.2013.09.009.

Halwachs-Baumann G. Concepts for Lean Laboratory Organization. *Journal of Medical Biochemistry*. 2010; 29(4):330-8. doi:10.2478/v10011-010-0036-5.

Haned H, Pène L, Lobry JR, Dufour AB, Pontier D. Estimating the Number of Contributors to Forensic DNA Mixtures: Does Maximum Likelihood Perform Better Than Maximum Allele Count? *Journal of Forensic Sciences*. 2011; 56(1):23-8. doi:10.1111/j.1556-4029.2010.01550.x.

Harrington HJ. *Business Process Improvement: The Breakthrough Strategy for Total Quality, Productivity, and Competitiveness*. McGraw Hill: New York, NY, 1991.

Hastie T, Tibshirani R, Friedman JH. *The Elements of Statistical Learning: Data Mining, Inference, and Prediction*. 2nd ed. Springer: New York, NY, 2009.

Hayeslip D, Debus-Sherrill S, Walsh KA. *Evaluation of the Forensic DNA Unit Efficiency Improvement Program*. Washington, DC. 2015. https://www.ojp.gov/pdffiles1/nij/grants/243332.pdf.

Henshall A. How to Use The Deming Cycle for Continuous Quality Improvement. Accessed March 27, 2024. https://www.process.st/deming-cycle/.

Hewson L, Goodman-Delahunty J. Using Multimedia to Support Jury Understanding of DNA Profiling Evidence. *Australian Journal of Forensic Sciences*. 2008; 40(1):55-64. doi:10.1080/00450610802050782.

Hicklin RA, Richetelli N, Emerick BL, Bever RA, Davoren JM. Variation in Assessments of Suitability and Number of Contributors for DNA Mixtures. *Forensic Science International: Genetics*. 2023; 65:102892. doi:10.1016/j.fsigen.2023.102892.

Hicklin RA, Winer KR, Kish PE, Parks CL, Chapman W, Dunagan K, Richetelli N, Epstein EG, Ausdemore MA, Busey TA. Accuracy and Reproducibility of Conclusions by Forensic Bloodstain Pattern Analysts. *Forensic Science International*. 2021; 325:110856. doi:10.1016/j.forsciint.2021.110856.

Hicks T, Biedermann A, de Koeijer JA, Taroni F, Champod C, Evett IW. The Importance of Distinguishing Information from Evidence/Observations When Formulating Propositions. *Science & Justice*. 2015; 55(6):520-5. doi:10.1016/j.scijus.2015.06.008.

Hicks T, Buckleton J, Castella V, Evett IW, Jackson G. A Logical Framework for Forensic DNA Interpretation. *Genes (Basel)*. 2022; 13(6):957. doi:10.3390/genes13060957.

Hicks T, Kerr Z, Pugh S, Bright JA, Curran JM, Taylor D, Buckleton J. Comparing Multiple POI to DNA Mixtures. *Forensic Science International: Genetics*. 2021; 52:102481. doi:10.1016/j.fsigen.2021.102481.

Himmelreich C. Germany's Phantom Serial Killer: A DNA Blunder. *Time*. 2009. Accessed March 27, 2024. https://content.time.com/time/world/article/0,8599,1888126,00.html

Hlinka V, Muharam I, Ientile VK. Chapter 11: Method Validation in Forensics and the Archaeological Sciences. In: Haslam M, Robertson G, Crowther A, Nugent S, Kirkwood L, eds. *Archaeological Science Under a Microscope: Studies in Residue and Ancient DNA Analysis in Honour of Thomas H Loy*. ANU Press: Canberra, Australia, 2009:151-8. doi:10.22459/TA30.07.2009.11.

Holland MM, Tiedge TM, Bender AJ, Gaston-Sanchez SA, McElhoe JA. MaSTR™: An Effective Probabilistic Genotyping Tool for Interpretation of STR Mixtures Associated with Differentially Degraded DNA. *International Journal of Legal Medicine*. 2022; 136(2):433-46. doi:10.1007/s00414-021-02771-0.

Holt TJ, Blevins KR, Foran DR, Smith RW. *Examination of the Conditions Affecting Forensic Scientists' Workplace Productivity and Occupational Stress - Executive Summary*. 2016. https://www.ojp.gov/pdffiles1/nij/grants/250234.pdf.

Hopwood AJ, Puch-Solis R, Tucker VC, Curran JM, Skerrett J, Pope S, Tully G. Consideration of the Probative Value of Single Donor 15-Plex STR Profiles in UK Populations and Its Presentation in UK Courts. *Science & Justice*. 2012; 52(3):185-90. doi:10.1016/j.scijus.2012.05.005.

Horjan I, Barbaric L, Mrsic G. Applicability of Three Commercially Available Kits for Forensic Identification of Blood Stains. *Journal of Forensic and Legal Medicine*. 2016; 38:101-5. doi:10.1016/j.jflm.2015.11.021.

Houck M, Speaker PJ, Fleming AS, Riley RA, Jr. The Balanced Scorecard: Sustainable Performance Assessment for Forensic Laboratories. *Science & Justice*. 2012; 52(4):209-16. doi:10.1016/j.scijus.2012.05.006.

Houck MM, Chin J, Swofford H, Gibb C. Registered Reports in Forensic Science. *Royal Society Open Science*. 2022; 9(11):221076. doi:10.1098/rsos.221076.

Houston Forensic Science Center. Record Search. Accessed March 27, 2024. https://records.hfscdiscovery.org/.

Howes LM, Kemp N. Discord in the Communication of Forensic Science: Can the Science of Language Help Foster Shared Understanding? *Journal of Language and Social Psychology*. 2016; 36(1):96-111. doi:10.1177/0261927x16663589.

Howes LM, Kirkbride KP, Kelty SF, Julian R, Kemp N. Forensic Scientists' Conclusions: How Readable Are They for Non-Scientist Report-Users? *Forensic Science International*. 2013; 231(1-3):102-12. doi:10.1016/j.forsciint.2013.04.026.

Huffman K, Hanson E, Ballantyne J. Probabilistic Genotyping of Single Cell Replicates from Complex DNA Mixtures Recovers Higher Contributor LRs Than Standard Analysis. *Science & Justice*. 2022; 62(2):156-63. doi:10.1016/j.scijus.2022.01.003.

Hundl C, Neuman M, Rairden A, Rearden P, Stout P. Implementation of a Blind Quality Control Program in a Forensic Laboratory. *Journal of Forensic Sciences*. 2020; 65(3):815-22. doi:10.1111/1556-4029.14259.

Iacob D, Fürst A, Hadrys T. A Machine Learning Model to Predict the Origin of Forensically Relevant Body Fluids. *Forensic Science International: Genetics Supplement Series*. 2019; 7(1):392-4. doi:10.1016/j.fsigss.2019.10.025.

Iacocca L. *Where Have All the Leaders Gone?* Scribner: New York, NY, 2008.

Ikumapayi OM, Akinlabi ET, Mwema FM, Ogbonna OS. Six Sigma Versus Lean Manufacturing - An Overview. *Materials Today: Proceedings*. 2020; 26:3275-81. doi:10.1016/j.matpr.2020.02.986.

Illuminating Engineering Society. *The Lighting Handbook: Reference and Application*. 10th ed. IES: New York, NY, 2011.

Imran MK, Ilyas M, Fatima T. Achieving Organizational Performance through Knowledge Management Capabilities: Mediating Role of Organizational Learning. *Pakistan Journal of Commerce and Social Sciences*. 2017; 11(1):106-25. doi:10419/188284.

Inal TC, Goruroglu Ozturk O, Kibar F, Cetiner S, Matyar S, Daglioglu G, Yaman A. Lean Six Sigma Methodologies Improve Clinical Laboratory Efficiency and Reduce Turnaround Times. *Journal of Clinical Laboratory Analysis*. 2018; 32(1):e22180. doi:10.1002/jcla.22180.

International Association for Identification. Certifications. Accessed March 27, 2024. https://www.theiai.org/certifications.php.

International Critical Incident Stress Foundation, Inc (ICISF). Certification of Knowledge in Critical Incident Stress Management (CCISM). Accessed March 27, 2024. https://cismcertifications.org/.

International Organization for Standardization (ISO). About ISO. Accessed March 27, 2024. https://www.iso.org/about-us.html.

International Organization for Standardization (ISO). *Conformity Assessment: General Requirements for the Competency of Proficiency Testing Providers, ISO/IEC 17043:2023*. 2023. https://www.iso.org/standard/80864.html.

International Organization for Standardization (ISO). *Conformity Assessment: Vocabulary and General Principles, ISO/IEC 17000:2020* 2004. https://www.iso.org/standard/73029.html.

International Organization for Standardization (ISO). *Forensic Sciences - Part 1: Terms and Definitions, ISO/IEC 21043-1:20018(En)*. 2018. https://www.iso.org/obp/ui/#iso:std:iso:21043:-1:ed-1:v1:en.

International Organization for Standardization (ISO). *Forensic Sciences - Part 2: Recognition, Recording, Collecting, Transport, and Storage of Items, ISO/IEC 21043-2:2018*. 2018. https://www.iso.org/standard/72041.html.

International Organization for Standardization (ISO). *General Requirements for the Competence of Testing and Calibration Laboratories, ISO/IEC 17025:2017*. 2017. https://www.iso.org/standard/66912.html.

International Organization for Standardization (ISO). International Electrotechnical Commission. Accessed March 27, 2024. https://www.iso.org/organization/70.html.

International Organization for Standardization (ISO). *Minimizing the Risk of Human DNA Contamination in Products Used to Collect, Store and Analyze Biological Material for Forensic Purposes. ISO 18385:2016* 2016. https://www.iso.org/standard/62341.html.

International Organization for Standardization (ISO). *Risk Management Guidelines, ISO/IEC 31000:2018*. 2018. https://www.iso.org/standard/65694.html.

International Symposium on Human Identification (ISHI) News. The Importance of Leadership Training in the Forensic Field. Accessed March 27, 2024. https://www.ishinews.com/the-importance-of-leadership-training-in-the-forensic-field/.

InVita Healthcare Technologies. DNA & Forensic Sample Management Solutions. Accessed March 27, 2024. https://www.invitahealth.com/solutions/dna-and-forensics/.

Ioannidis JPA. Correction: Why Most Published Research Findings Are False. *PLoS Medicine*. 2022; 19(8):e1004085. doi:10.1371/journal.pmed.1004085.

Ip SCY, Lin S-W, Lai K-M. An Evaluation of the Performance of Five Extraction Methods: Chelex® 100, QIAamp® DNA Blood Mini Kit, QIAamp® DNA Investigator Kit, QIAsymphony® DNA Investigator® Kit and DNA IQ. *Science & Justice*. 2015; 55(3):200-8. doi:10.1016/j.scijus.2015.01.005.

Jackson G. The Scientist and the Scales of Justice. *Science & Justice*. 2000; 40(2):81-5. doi:10.1016/S1355-0306(00)71947-2.

Jackson G, Biedermann A. "Source" or "Activity" What Is the Level of Issue in a Criminal Trial? *Significance*. 2019; 16(2):36-9. doi:10.1111/j.1740-9713.2019.01253.x.

Jackson G, Jones PJ. Case Assessment and Interpretation. *Wiley Encyclopedia of Forensic Science*. 2009; 2:483-96. doi:10.1002/9780470061589.fsa124.

Jackson G, Jones S, Booth G, Champod C, Evett IW. The Nature of Forensic Science Opinion - a Possible Framework to Guide Thinking and Practice in Investigations and in Court Proceedings. *Science & Justice*. 2006; 46(1):33-44. doi:10.1016/s1355-0306(06)71565-9.

Jackson T, Dawson R, Wilson D. Reducing the Effect of Email Interruptions on Employees. *International Journal of Information Management*. 2003; 23(1):55-65. doi:10.1016/s0268-4012(02)00068-3.

Jeanguenat AM, Budowle B, Dror IE. Strengthening Forensic DNA Decision Making through a Better Understanding of the Influence of Cognitive Bias. *Science & Justice*. 2017; 57(6):415-20. doi:10.1016/j.scijus.2017.07.005.

Johnston N. The Paradox of Rules: Procedural Drift in Commercial Aviation. Proceedings of the Twelfth International Symposium on Aviation Psychology, Dayton, OH, 2003. https://cognitivesystemsdesign.net/Papers/Johnston%20(2003).pdf

Jones D. The Cognitive Psychology of Auditory Distraction: The 1997 BPS Broadbent Lecture. *British Journal of Psychology*. 1999; 90(2):167-87. doi:10.1348/000712699161314.

Kalafut T, Bright JA, Taylor D, Buckleton J. Investigation into the Effect of Mixtures Comprising Related People on Non-Donor Likelihood Ratios, and Potential Practises to Mitigate Providing Misleading Opinions. *Forensic Science International: Genetics*. 2022; 59:102691. doi:10.1016/j.fsigen.2022.102691.

Kalafut T, Pugh S, Gill P, Abbas S, Semaan M, Mansour I, Curran JM, Bright JA, Hicks T, Wivell R, Buckleton J. A Mixed DNA Profile Controversy Revisited. *Journal of Forensic Sciences*. 2022; 67(1):128-35. doi:10.1111/1556-4029.14912.

Kansas City Missouri Police Department. Crime Lab. Accessed March 27, 2024. https://www.kcpd.org/crime/crime-lab/.

Kassin SM, Dror IE, Kukucka J. The Forensic Confirmation Bias: Problems, Perspectives, and Proposed Solutions. *Journal of Applied Research in Memory and Cognition*. 2013; 2(1):42-52. doi:10.1016/j.jarmac.2013.01.001.

Kaye DH. The Design of "The First Experimental Study Exploring DNA Interpretation". *Science & Justice*. 2012; 52(2):126-7; author reply 128-30. doi:10.1016/j.scijus.2011.10.003.

Kaye DH. *The Double Helix and the Law of Evidence*. Harvard University Press: Cambridge, MA, 2010.

Kaye DH. The Expected Value Fallacy in State v. Wright. *Jurimetrics: The Journal of Law, Science, and Technology*. 2011; 51(4):1921082. doi:ssrn.com/abstract=1921082.

Kaye DH. Identification, Individualization and Uniqueness: What's the Difference? *Law, Probability and Risk*. 2009; 8(2):85-94. doi:10.1093/lpr/mgp018.

Kaye DH. Plemel as a Primer on Proving Paternity. *Willamette Law Review*. 1988; 24(4):867-83.

Kaye DH. Probability, Individualization, and Uniqueness in Forensic Science Evidence: Listening to the Academics. *Brooklyn Law Review*. 2010; 75(4):1163-85.

Kaye DH. The Ultimate Opinion Rule and Forensic Science Identification. *Jurimetrics: The Journal of Law, Science, and Technology*. 2020; 60(2):175-85. doi:10.2139/ssrn.3483226.

Kaye DH, Bernstein DE, Mnookin JL. *The New Wigmore: A Treatise on Evidence - Expert Evidence*. 3rd ed. Wolters Kluwer Law & Business: 2020.

Kaye DH, Sensabaugh G. Reference Guide on DNA Identification Evidence. *Reference Manual on Scientific Evidence*. 3rd ed. The National Academies Press: Washington, DC, 2011. doi:10.17226/13163.

Keel P. Psychological Stress Caused by Work: Burnout Syndrome. *Soz Praventivmed*. 1993; 38(2):S131-2. Psychische Belastungen durch die Arbeit: Burnout-Syndrom. doi:10.1007/BF01305364.

Keith N, Frese M. Enhancing Firm Performance and Innovativeness through Error Management Culture. In: Ashkanasy NM, Wilderom CPM, Peterson MF, eds. *The Handbook of Organizational Culture and Climate*. 2nd ed. SAGE Publications, Inc: Thousand Oaks, CA, 2011. doi:10.4135/9781483307961.

Kelly H, Bright JA, Kruijver M, Cooper S, Taylor D, Duke K, Strong M, Beamer V, Buettner C, Buckleton J. A Sensitivity Analysis to Determine the Robustness of STRmix with Respect to Laboratory Calibration. *Forensic Science International: Genetics*. 2018; 35:113-22. doi:10.1016/j.fsigen.2018.04.009.

Kelly H, Coble M, Kruijver M, Wivell R, Bright JA. Exploring Likelihood Ratios Assigned for Siblings of the True Mixture Contributor as an Alternate Contributor. *Journal of Forensic Sciences*. 2022; 67(3):1167-75. doi:10.1111/1556-4029.15020.

Kelly H, Kerr Z, Cheng K, Kruijver M, Bright JA. Developmental Validation of a Software Implementation of a Flexible Framework for the Assignment of Likelihood Ratios for

Forensic Investigations. *Forensic Science International: Reports*. 2021; 4:100231. doi:10.1016/j.fsir.2021.100231.

Khan K, Carriquiry AL. Shining a Light on Forensic Black-Box Studies. *Statistics and Public Policy*. 2023; 10(1):2216748. doi:10.1080/2330443x.2023.2216748.

Khoshbakht M, Rasheed EO, Baird G. Office Distractions and the Productivity of Building Users: The Effect of Workgroup Sizes and Demographic Characteristics. *Buildings*. 2021; 11(2):55. doi:10.3390/buildings11020055.

Kilberger KB. Something Doesn't Add Up: Solving DNA Forensic Science Statistical Fallacies in Trial Testimony. *Vanderbilt Journal of Entertainment and Technology Law*. 2023; 25(1):181-209.

Kim CS, Spahlinger DA, Kin JM, Coffey RJ, Billi JE. Implementation of Lean Thinking: One Health System's Journey. *The Joint Commission Journal on Quality and Patient Safety*. 2009; 35(8):406-13. doi:10.1016/S1553-7250(09)35057-6.

Klentz BA, Winters GM, Chapman JE. The CSI Effect and the Impact of DNA Evidence on Mock Jurors and Jury Deliberations. *Psychology, Crime & Law*. 2020; 26(6):552-70. doi:10.1080/1068316x.2019.1708353.

Kloosterman A, Sjerps M, Quak A. Error Rates in Forensic DNA Analysis: Definition, Numbers, Impact and Communication. *Forensic Science International: Genetics*. 2014; 12:77-85. doi:10.1016/j.fsigen.2014.04.014.

Koehler JJ. If the Shoe Fits They Might Acquit: The Value of Forensic Science Testimony. *Journal of Empirical Legal Studies*. 2011; 8(s1):21-48. doi:10.1111/j.1740-1461.2011.01225.x.

Koehler JJ. The Influence of Prior Beliefs on Scientific Judgments of Evidence Quality. *Organizational Behavior and Human Decision Processes*. 1993; 56(1):28-55. doi:10.1006/obhd.1993.1044.

Koehler JJ. Intuitive Error Rate Estimates for the Forensic Sciences. *Jurimetrics: The Journal of Law, Science, and Technology*. 2017; 57(2):153-68.

Koehler JJ, Chia A, Lindsey S. The Random Match Probability in DNA Evidence: Irrelevant and Prejudicial? *Jurimetrics: The Journal of Law, Science, and Technology*. 2009; 35(2):201-19.

Koehler JJ, Schweitzer NJ, Saks MJ, McQuiston DE. Science, Technology, or the Expert Witness: What Influences Jurors' Judgments About Forensic Science Testimony? *Psychology, Public Policy, and Law*. 2016; 22(4):401-13. doi:10.1037/law0000103.

Kokshoorn B, Luijsterburg M. Reporting on Forensic Biology Findings Given Activity Level Issues in the Netherlands. *Forensic Science International*. 2023; 343:111545. doi:10.1016/j.forsciint.2022.111545.

Krcmar M, Ewoldsen DR, Koerner A. *Communication Science Theory and Research: An Advanced Introduction*. Routledge: New York, NY, 2016.

Kroemer KHE, Grandjean E. *Fitting The Task to The Human: A Textbook of Occupational Ergonomics*. 5th ed. CRC Press: London, UK, 1997. doi:10.1201/9780367807337.

Kruijver M, Curran JM. The Number of Alleles in DNA Mixtures with Related Contributors. *Forensic Science International: Genetics*. 2022; 61:102748. doi:10.1016/j.fsigen.2022.102748.

Kruijver M, Kelly H, Cheng K, Lin MH, Morawitz J, Russell L, Buckleton J, Bright JA. Estimating the Number of Contributors to a DNA Profile Using Decision Trees. *Forensic Science International: Genetics*. 2021; 50:102407. doi:10.1016/j.fsigen.2020.102407.

Kukucka J, Hiley A, Kassin SM. Forensic Confirmation Bias: Do Jurors Discount Examiners Who Were Exposed to Task-Irrelevant Information? *Journal of Forensic Sciences*. 2020; 65(6):1978-90. doi:10.1111/1556-4029.14546.

Laboratory for Forensic Technology Development & Integration. PROVEDIt Database. Rutgers University. Accessed March 27, 2024. https://lftdi.camden.rutgers.edu/provedit/files.

Lackey A. Tips and Tricks for Using GeneMapper ID-X Software. ThermoFisher Scientific. Accessed March 27, 2024. https://www.thermofisher.com/blog/behindthebench/tips-and-tricks-for-using-genemapper-id-x-software/.

Langenburg G. Addressing Potential Observer Effects in Forensic Science: A Perspective from a Forensic Scientist Who Uses Linear Sequential Unmasking Techniques. *Australian Journal of Forensic Sciences*. 2017; 49(5):548-63. doi:10.1080/00450618.2016.1259433.

Lapointe M, Rogic A, Bourgoin S, Jolicoeur C, Seguin D. Leading-Edge Forensic DNA Analyses and the Necessity of Including Crime Scene Investigators, Police Officers and Technicians in a DNA Elimination Database. *Forensic Science International: Genetics*. 2015; 19:50-5. doi:10.1016/j.fsigen.2015.06.002.

Las Vegas Metropolitan Police Department Forensic Laboratory. *Biology/DNA Detail Quality Manual*. 2023. https://www.lvmpd.com/home/showpublisheddocument/5200/638387677587930000.

Law Enforcement Innovation Center (LEIC). UT National Forensic Academy - 10 Week Program. Accessed March 26, 2024. https://leic.tennessee.edu/home/training/forensic-training/national-forensic-academy/.

Lawrence TB, Mauws MK, Dyck B, Kleysen RF. The Politics of Organizational Learning: Integrating Power into the 4I Framework. *Academy of Management Review*. 2005; 30(1):180-91. doi:10.5465/amr.2005.15281451.

Lawrenson JG, Hull CC, Downie LE. The Effect of Blue-Light Blocking Spectacle Lenses on Visual Performance, Macular Health and the Sleep-Wake Cycle: A Systematic Review of the Literature. *Ophthalmic and Physiological Optics*. 2017; 37(6):644-54. doi:10.1111/opo.12406.

Levin AP, Putney H, Crimmins D, McGrath JG. Secondary Traumatic Stress, Burnout, Compassion Satisfaction, and Perceived Organizational Trauma Readiness in Forensic Science

Professionals. *Journal of Forensic Sciences*. 2021; 66(5):1758-69. doi:10.1111/1556-4029.14747.

Lin M-H, Bright JA, Pugh SN, Buckleton J. The Interpretation of Mixed DNA Profiles from a Mother, Father, and Child Trio. *Forensic Science International: Genetics*. 2020; 44:102175. doi:10.1016/j.fsigen.2019.102175.

Lin M-H, Lee S-I, Zhang X, Russell L, Kelly H, Cheng K, Cooper S, Wivell R, Kerr Z, Morawitz J, Bright JA. Developmental Validation of FaSTR™ DNA: Software for the Analysis of Forensic DNA Profiles. *Forensic Science International: Reports*. 2021; 3:100217. doi:10.1016/j.fsir.2021.100217.

Lindley DV. A Problem in Forensic Science. *Biometrika*. 1977; 64(2):207-13. doi:10.1093/biomet/64.2.207.

Lindley DV. *Understanding Uncertainty*. John Wiley & Sons, Ltd.: Hoboken, NJ, 2006.

Ludeman MJ, Zhong C, Mulero JJ, Lagace RE, Hennessy LK, Short ML, Wang DY. Developmental Validation of Globalfiler PCR Amplification Kit: A 6-Dye Multiplex Assay Designed for Amplification of Casework Samples. *International Journal of Legal Medicine*. 2018; 132(6):1555-73. doi:10.1007/s00414-018-1817-5.

Lyle JR, Guttman B, Butler JM, Sauerwein K, Reed C, Lloyd C. *Digital Investigation Techniques: A NIST Scientific Foundation Review*. National Institute of Standards and Technology. 2022. *NIST IR 8354*. doi: 10.6028/NIST.IR.8354.

MacEwen BT, MacDonald DJ, Burr JF. A Systematic Review of Standing and Treadmill Desks in the Workplace. *Preventive Medicine*. 2015; 70(1):50-8. doi:10.1016/j.ypmed.2014.11.011.

Maeder EM, Ewanation LA, Monnink J. Jurors' Perceptions of Evidence: The Relative Influence of DNA and Eyewitness Testimony When Presented by Opposing Parties. *Journal of Police and Criminal Psychology*. 2016; 32(1):33-42. doi:10.1007/s11896-016-9194-9.

Maeder EM, McManus LA, McLaughlin KJ, Yamamoto S, Stewart H, Walla P. Jurors' Perceptions of Scientific Testimony: The Role of Gender and Testimony Complexity in Trials Involving DNA Evidence. *Cogent Psychology*. 2016; 3(1):1264657. doi:10.1080/23311908.2016.1264657.

Maradona AF. A Qualitative Exploration of Heuristics and Cognitive Biases in Auditor Judgements. *Accountability*. 2020; 9(2):94-112. doi:10.32400/ja.30634.9.2.2020.94-112.

Marciano MA, Adelman JD. PACE: Probabilistic Assessment for Contributor Estimation- a Machine Learning-Based Assessment of the Number of Contributors in DNA Mixtures. *Forensic Science International: Genetics*. 2017; 27:82-91. doi:10.1016/j.fsigen.2016.11.006.

Marciano MA, Maynard HP. Enhancing Research and Collaboration in Forensic Science: A Primer on Data Sharing. *Forensic Science International: Synergy*. 2023; 6:100323. doi:10.1016/j.fsisyn.2023.100323.

Marquis R, Biedermann A, Cadola L, Champod C, Gueissaz L, Massonnet G, Mazzella WD, Taroni F, Hicks T. Discussion on How to Implement a Verbal Scale in a Forensic Laboratory: Benefits, Pitfalls and Suggestions to Avoid Misunderstandings. *Science & Justice*. 2016; 56(5):364-70. doi:10.1016/j.scijus.2016.05.009.

Marshall University. Forensic Science Graduate Program: DNA Technical Leader Assistance Program (TAP). Accessed March 27, 2024. https://www.marshall.edu/forensics/tap.

Martire KA. Clear Communication through Clear Purpose: Understanding Statistical Statements Made by Forensic Scientists. *Australian Journal of Forensic Sciences*. 2018; 50(6):619-27. doi:10.1080/00450618.2018.1439101.

Martire KA, Ballantyne KN, Bali A, Edmond G, Kemp RI, Found B. Forensic Science Evidence: Naive Estimates of False Positive Error Rates and Reliability. *Forensic Science International*. 2019; 302:109877. doi:10.1016/j.forsciint.2019.109877.

Martire KA, Kemp RI, Newell BR. The Psychology of Interpreting Expert Evaluative Opinions. *Australian Journal of Forensic Sciences*. 2013; 45(3):305-14. doi:10.1080/00450618.2013.784361.

Martire KA, Kemp RI, Sayle M, Newell BR. On the Interpretation of Likelihood Ratios in Forensic Science Evidence: Presentation Formats and the Weak Evidence Effect. *Forensic Science International*. 2014; 240:61-8. doi:10.1016/j.forsciint.2014.04.005.

Martire KA, Kemp RI, Watkins I, Sayle MA, Newell BR. The Expression and Interpretation of Uncertain Forensic Science Evidence: Verbal Equivalence, Evidence Strength, and the Weak Evidence Effect. *Law and Human Behavior*. 2013; 37(3):197-207. doi:10.1037/lhb0000027.

Martire KA, Watkins I. Perception Problems of the Verbal Scale: A Reanalysis and Application of a Membership Function Approach. *Science & Justice*. 2015; 55(4):264-73. doi:10.1016/j.scijus.2015.01.002.

Massachusetts State Police Crime Laboratory. Laboratory Materials Request Policy. Accessed March 27, 2024. https://www.mass.gov/doc/laboratory-materials-request-policy-0/download.

Mattijssen EJ, Kerkhoff W, Berger CEH, Dror IE, Stoel RD. Implementing Context Information Management in Forensic Casework: Minimizing Contextual Bias in Firearms Examination. *Science & Justice*. 2016; 56(2):113-22. doi:10.1016/j.scijus.2015.11.004.

Mayer RE, Moreno R. Nine Ways to Reduce Cognitive Load in Multimedia Learning. *Educational Psychologist*. 2010; 38(1):43-52. doi:10.1207/s15326985ep3801_6.

McAndrew WP, Roth MG. Up from "Arts and Crafts": Division of Labor in Forensic Science Laboratories. *Forensic Science Policy & Management: An International Journal*. 2016; 7(3-4):61-8. doi:10.1080/19409044.2016.1153173.

McCarthy Wilcox A, NicDaeid N. Jurors' Perceptions of Forensic Science Expert Witnesses: Experience, Qualifications, Testimony Style and Credibility. *Forensic Science International*. 2018; 291:100-8. doi:10.1016/j.forsciint.2018.07.030.

McInerny GJ, Chen M, Freeman R, Gavaghan D, Meyer M, Rowland F, Spiegelhalter DJ, Stefaner M, Tessarolo G, Hortal J. Information Visualisation for Science and Policy: Engaging Users and Avoiding Bias. *Trends in Ecology & Evolution*. 2014; 29(3):148-57. doi:10.1016/j.tree.2014.01.003.

McKenna PJ. Strategies for Overcoming Obstacles to Change. *Of Counsel*. 2017; 36(7):6-12. doi:proquest.com/trade-journals/strategies-overcoming-obstacles-change/docview/1915769056/se-2.

McLendon M, Jones II JP. What's Happening (or Not?) with Forensic Science Training for Officers of the Court. 75th Annual American Academy of Forensic Sciences Symposium, Orlando, FL 2023.

McQuiston-Surrett D, Saks MJ. Communicating Opinion Evidence in the Forensic Identification Sciences: Accuracy and Impact. *Hastings Law Journal*. 2008; 59(5):1159-90.

McQuiston-Surrett D, Saks MJ. The Testimony of Forensic Identification Science: What Expert Witnesses Say and What Factfinders Hear. *Law and Human Behavior*. 2009; 33(5):436-53. doi:10.1007/s10979-008-9169-1.

Meakin G, Jamieson A. DNA Transfer: Review and Implications for Casework. *Forensic Science International: Genetics*. 2013; 7(4):434-43. doi:10.1016/j.fsigen.2013.03.013.

Meakin GE, Kokshoorn B, van Oorschot RAH, Szkuta B. Evaluating Forensic DNA Evidence: Connecting the Dots. *WIREs Forensic Science*. 2020; 3(4):e1404. doi:10.1002/wfs2.1404.

Melbourn H, Smith G, McFarland J, Rogers M, Wieland K, DeWilde D, Lighthart S, Quinn M, Baxter A, Quarino L. Mandatory Certification of Forensic Science Practitioners in the United States: A Supportive Perspective. *Forensic Science International: Synergy*. 2019; 1:161-9. doi:10.1016/j.fsisyn.2019.08.001.

Mellor D. Improving Norms in Research Culture to Incentivize Transparency and Rigor. *Educational Psychologist*. 2021; 56(2):122-31. doi:10.1080/00461520.2021.1902329.

Member Resource Committee Stress/Trauma Working Group. *Management Detection and Mitigation of Stress, Vicarious Trauma, and Burnout in Forensic Practitioners*. 2020. https://www.ascld.org/wp-content/uploads/2020/04/Management-Detection-and-Mitigation-of-Stress-Vicarious-Trauma-and-Burnout-in-Forensic-Practitioners-February-2020.pdf.

Mills E, Borg N. Trends in Recommended Illuminance Levels: An International Comparison. *Journal of the Illuminating Engineering Society*. 2013; 28(1):155-63. doi:10.1080/00994480.1999.10748262.

Mitchell G, Garrett BL. Battling to a Draw: Defense Expert Rebuttal Can Neutralize Prosecution Fingerprint Evidence. *Applied Cognitive Psychology*. 2021; 35(4):976-87. doi:10.1002/acp.3824.

Mnookin JL, Cole SA, Dror IE, Fisher BAJ, Houck M, Inman K, Kaye DH, Koehler J, Langenburg G, Risinger M, Rudin N, Siegel D, Stoney DA. The Need for a Research Culture in the Forensic Sciences. *UCLA Law Review*. 2011; 58(3):725-80.

Money N, Moore M, Brown D, Kasper K, Roeder J, Bartone P, Bates M. *Best Practices Identified for Peer Support Programs*. Defense Centers of Excellence for Psychological Health & Traumatic Brain Injury. 2011. https://www.mhanational.org/sites/default/files/Best_Practices_Identified_for_Peer_Support_Programs_Jan_2011.pdf.

Monteiro EC, Mari L. Preliminary Notes on Metrological Reliability. XXI IMEKO World Congress, Prague, Czech Republic 2015. https://www.imeko.org/publications/wc-2015/IMEKO-WC-2015-TC6-173.pdf

Moretti TR, Baumstark AL, Defenbaugh DA, Keys KM, Brown AL, Budowle B. Validation of STR Typing by Capillary Electrophoresis. *Journal of Forensic Sciences*. 2001; 46(3):661-76. doi:10.1520/jfs15019j.

Moretti TR, Baumstark AL, Defenbaugh DA, Keys KM, Smerick JB, Budowle B. Validation of Short Tandem Repeats (STRs) for Forensic Usage: Performance Testing of Fluorescent Multiplex STR Systems and Analysis of Authentic and Simulated Forensic Samples. *Journal of Forensic Sciences*. 2001; 46(3):647-60. doi:10.1520/JFS15018J.

Moretti TR, Just RS, Kehl SC, Willis LE, Buckleton J, Bright JA, Taylor DA, Onorato AJ. Internal Validation of STRmix™ for the Interpretation of Single Source and Mixed DNA Profiles. *Forensic Science International: Genetics*. 2017; 29:126-144. doi:10.1016/j.fsigen.2017.04.004.

Morgan J. Wrongful Convictions and Claims of False or Misleading Forensic Evidence. *Journal of Forensic Sciences*. 2023; 68(3):908-61. doi:10.1111/1556-4029.15233.

Morrison A. New York City Agency Has Underreported Lab Errors in DNA Database It Oversees. The Appeal. Feb 24, 2020. Accessed March 27, 2024. https://theappeal.org/new-york-city-dna-database-lab-errors/

Morrison GS, Neumann C, Geoghegan PH. Vacuous Standards — Subversion of the OSAC Standards-Development Process. *Forensic Science International: Synergy*. 2020; 2:206-9. doi:10.1016/j.fsisyn.2020.06.005.

Mullen C, Spence D, Moxey L, Jamieson A. Perception Problems of the Verbal Scale. *Science & Justice*. 2014; 54(2):154-8. doi:10.1016/j.scijus.2013.10.004.

Müller BJ, Liebl A, Martin N. Influence of Active-Noise-Cancelling Headphones on Cognitive Performance and Employee Satisfaction in Open Space Offices. 23rd International Congress on Acoustics, Aachen, Germany 2019. https://pub.dega-akustik.de/ICA2019/data/articles/000062.pdf

Murphy E, Thompson WC. Common Errors and Fallacies in Forensic DNA Statistics: An Amicus Brief in McDaniel v. Brown. *Criminal Law Bulletin*. 2010; 46:709.

Murrie DC, Boccaccini MT. Adversarial Allegiance among Expert Witnesses. *Annual Review of Law and Social Science*. 2015; 11:37-55. doi:10.1146/annurev-lawsocsci-120814-121714.

Murrie DC, Gardner BO, Kelley S, Dror IE. Perceptions and Estimates of Error Rates in Forensic Science: A Survey of Forensic Analysts. *Forensic Science International*. 2019; 302:109887. doi:10.1016/j.forsciint.2019.109887.

NASA Aviation Safety Reporting System (ASRS). *Database Report Set - Checklist Incidents*. 2022. https://asrs.arc.nasa.gov/docs/rpsts/chklist.pdf.

National Association of Testing Authorities. *Guidelines for the Validation and Verification of Quantitative and Qualitative Test Methods. Technical Note 17*. 2012. https://www.demarcheiso17025.com/document/Guidelines%20for%20the%20validation%20and%20verification%20of%20quantitative%20and%20qualitative%20test%20methods.pdf.

National Association of Testing Authorities. *Specific Accreditation Criteria ISO/IEC 17025 Application Document Legal (Including Forensic Science) - Appendix*. 2023. https://nata.com.au/files/2021/05/Forensic-Science-ISO-IEC-17025-Appendix-effective-feb-2020.pdf.

National Commission on Forensic Science. *National Code of Ethics and Professional Responsibility for the Forensic Sciences*. n.d. https://www.justice.gov/usdoj-media/ncfs/media/898006/dl.

National Commission on Forensic Science. *Recommendation to the Attorney General Documentation, Case Record, and Report Contents*. 2016. https://www.justice.gov/archives/ncfs/page/file/905536/download.

National Commission on Forensic Science. *Recommendation to the Attorney General: Root Cause Analysis (RCA) in Forensic Science*. 2015. https://www.justice.gov/archives/ncfs/file/786581/download.

National Commission on Forensic Science. *Views of the Commission Inconsistent Terminology*. 2015. https://www.justice.gov/archives/ncfs/page/file/1004446/download.

National Commission on Forensic Science. *Views of the Commission: Certification of Forensic Science Practitioners*. 2016. https://www.justice.gov/ncfs/page/file/905897/dl.

National Commission on Forensic Science. *Views of the Commission: Defining Forensic Science and Related Terms*. 2016. https://www.justice.gov/sites/default/files/ncfs/pages/attachments/2015/04/16/final_draft_for_ncfs_vote-defining_forensic_science_and_related_terms.pdf.

National Commission on Forensic Science. *Views of the Commission: Optimizing Human Performance in Crime Laboratories through Testing and Feedback*. 2016. https://www.justice.gov/archives/ncfs/page/file/864776/download.

National Commission on Forensic Science. *Views of the Commission: Proficiency Testing in Forensic Science*. 2016. https://www.justice.gov/ncfs/page/file/839691/dl.

National Commission on Forensic Science. *Views of the Commission: Use of Checklists in Forensic Science*. 2017. https://www.justice.gov/archives/ncfs/page/file/1004656/dl.

National Institute of Justice (NIJ). *Education and Training in Forensic Science: A Guide for Forensic Science Laboratories, Educational Institutions, and Students*. 2004. https://www.ojp.gov/pdffiles1/nij/203099.pdf.

National Institute of Justice (NIJ). Forensic Science Strategic Research Plan, 2022-2026. Accessed March 27, 2024. https://nij.ojp.gov/topics/articles/forensic-sciences-strategic-research-plan-2022-2026#strategic-priority-iv-cultivate-a-diverse-highly-skilled-forensi.

National Institute of Justice (NIJ). *Forensic Sciences: Review of Status and Needs*. 1999. 94-IJ-R-004. https://www.ojp.gov/pdffiles1/173412.pdf.

National Institute of Justice (NIJ). NIJ FY24 Research and Evaluation for the Testing and Interpretation of Physical Evidence in Publicly Funded Forensic Laboratories. Accessed March 27, 2024. https://nij.ojp.gov/funding/opportunities/nij-fy24-public-labs.

National Institute of Justice (NIJ). Research and Evaluation of the Implementation and Use of Continuous Probabilistic Genotyping Software to Improve the Interpretation of Forensic DNA Mixtures. Accessed March 27, 2024. https://nij.ojp.gov/funding/awards/15pnij-21-gg-02710-slfo.

National Institute of Justice (NIJ). The Slow but Steady March Towards a More Reliable Forensic Science. Accessed March 27, 2024. https://nij.ojp.gov/topics/articles/slow-steady-march-towards-more-reliable-forensic-science.

National Institute of Standards and Technology (NIST). Forensic Science Program. Accessed March 27, 2024. https://www.nist.gov/spo/forensic-science-program.

National Institute of Standards and Technology (NIST). Houston Forensic Science Center to Voluntarily Adopt OSAC Standards. Accessed March 27, 2024. https://www.nist.gov/news-events/news/2018/12/houston-forensic-science-center-voluntarily-adopt-osac-standards.

National Institute of Standards and Technology (NIST). NIST Research Grade Test Material (RGTM) 10235: Forensic DNA Resource Samples, Information and Ordering. Accessed March 27, 2024. https://strbase.nist.gov/Information/RGTM_10235.

National Institute of Standards and Technology (NIST). NIST Store: Forensic DNA Resource Samples. 2024, Accessed Feb 5, 2024. https://shop.nist.gov/ccrz__ProductDetails?sku=10235&cclcl=en_US.

National Institute of Standards and Technology (NIST). The Organization of Scientific Area Committees for Forensic Science. Accessed March 27, 2024. https://www.nist.gov/organization-scientific-area-committees-forensic-science.

This publication is available free of charge from: https://doi.org/10.6028/NIST.IR.8503

National Institute of Standards and Technology (NIST). Two New Forensic DNA Standards Added to the OSAC Registry. Accessed March 27, 2024. https://www.nist.gov/news-events/news/2020/05/two-new-forensic-dna-standards-added-osac-registry.

National Research Council. *Integrity in Scientific Research: Creating an Environment That Promotes Responsible Conduct*. The National Academies Press: Washington, DC, 2002. doi:10.17226/10430.

National Research Council, Committee on Identifying the Needs of the Forensic Science Community. *Strengthening Forensic Science in the United States: A Path Forward*. The National Academies Press: Washington, DC, 2009. doi:10.21428/cb6ab371.b2d683d2.

Nelson A. Memorandum for the Heads of Executive Departments and Agencies: Ensuring Free, Immediate, and Equitable Access to Federally Funded Research. Office of Science and Technology Policy, Executive Office of the President. Accessed March 27, 2024. https://www.whitehouse.gov/wp-content/uploads/2022/08/08-2022-OSTP-Public-Access-Memo.pdf

Netherlands Forensic Institute. Research and Innovation. Netherlands Forensic Institute, Ministry of Justice and Security. Accessed March 27, 2024. https://www.forensicinstitute.nl/research-and-innovation.

New York Criminal Procedure Law. *CPL Article 245*. Accessed March 27, 2024. https://ypdcrime.com/cpl/article245.php.

New York State Senate. *Senate Bill S8117*. 2016. Accessed March 27, 2024. https://www.nysenate.gov/legislation/bills/2015/S8117.

Newman J, Dawley D, Speaker PJ. Strategic Management of Forensic Laboratory Resources: From Project FORESIGHT Metrics to the Development of Action Plans. *Forensic Science Policy & Management: An International Journal*. 2011; 2(4):164-74. doi:10.1080/19409044.2012.693571.

Nickerson RS. Confirmation Bias: A Ubiquitous Phenomenon in Many Guises. *Review of General Psychology*. 1998; 2(2):175-220. doi:10.1037/1089-2680.2.2.175.

Nisbett RE, Wilson TD. The Halo Effect: Evidence for Unconscious Alteration of Judgments. *Journal of Personality and Social Psychology*. 1977; 35:250-6. doi:10.1037/0022-3514.35.4.250.

Noël S, Noël J, Granger D, Lefebvre JF, Seguin D. STRmix™ Put to the Test: 300 000 Non-Contributor Profiles Compared to Four-Contributor DNA Mixtures and the Impact of Replicates. *Forensic Science International: Genetics*. 2019; 41:24-31. doi:10.1016/j.fsigen.2019.03.017.

Norcini JJ. Peer Assessment of Competence. *Medical Education*. 2003; 37(6):539-43. doi:10.1046/j.1365-2923.2003.01536.x.

Norsworthy S, Lun DS, Grgicak CM. Determining the Number of Contributors to DNA Mixtures in the Low-Template Regime: Exploring the Impacts of Sampling and Detection Effects. *Legal Medicine*. 2018; 32:1-8. doi:10.1016/j.legalmed.2018.02.001.

Office for Victims of Crime. The Vicarious Trauma Toolkit: Blueprint for a Vicarious Trauma-Informed Organization Accessed March 27, 2024. https://ovc.ojp.gov/program/vtt/introduction.

Office of Legal Policy. Forensic Science. Accessed March 27, 2024. https://www.justice.gov/olp/forensic-science.

Office of Management and Budget, Executive Office of the President. Final Information Quality Bulletin for Peer Review. Accessed March 27, 2024. https://www.federalregister.gov/documents/2005/01/14/05-769/final-information-quality-bulletin-for-peer-review.

Office of the Law Revision Counsel of the United States House of Representatives. *34 USC 12591: Part A–DNA Identification: Quality Assurance and Proficiency Testing Standards*. 2023. https://uscode.house.gov/view.xhtml?req=granuleid%3AUSC-prelim-title34-chapter121-subchapter8-partA&edition=prelim.

Office of the Law Revision Counsel of the United States House of Representatives. *34 USC 12592: Index to Facilitate Law Enforcement Exchange of DNA Identification Information*. 2023. https://uscode.house.gov/view.xhtml?req=granuleid:USC-prelim-title34-section12592&num=0&edition=prelim#:~:text=34%20USC%2012592%3A%20Index%20to%20facilitate%20law%20enforcement,those%20laws%20in%20effect%20on%20September%2029%2C%202022.

Ommen DM, Saunders CP, Neumann C. An Argument against Presenting Interval Quantifications as a Surrogate for the Value of Evidence. *Science & Justice*. 2016; 56(5):383-7. doi:10.1016/j.scijus.2016.07.001.

Organization of Scientific Area Committees (OSAC). *Human Forensic DNA Analysis Process Map*. 2022. https://www.nist.gov/system/files/documents/2022/05/05/OSAC%20Forensic%20Biology%20Process%20Map_5.5.22.pdf.

Organization of Scientific Area Committees (OSAC). *Informative Literature for Forensic Biology and DNA*. 2020. https://www.nist.gov/system/files/documents/2021/03/26/Informative%20Literature%20for%20Forensic%20Biology%20and%20DNA%20-10-26-20.pdf.

Organization of Scientific Area Committees (OSAC). *OSAC 2020-N-0007, Best Practice Recommendations for the Management and Use of Quality Assurance DNA Elimination Databases in Forensic DNA Analysis*. 2021. https://www.nist.gov/system/files/documents/2021/04/01/OSAC%202020-N-0007_Best%20Practice%20Recommendations%20for%20the%20Management%20and%20Use%20of%20Quality%20Assurance%20DNA%20Elimination%20Databases%20in%20Forensic%20DNA%20Analysis_FINAL%20OSAC%20PROPOSED%20REG.pdf.

This publication is available free of charge from: https://doi.org/10.6028/NIST.IR.8503

Organization of Scientific Area Committees (OSAC). *OSAC Preferred Terms*. 2023. https://www.nist.gov/system/files/documents/2023/07/21/OSAC%20Preferred%20Terms_July%202023.pdf.

Organization of Scientific Area Committees (OSAC). OSAC Registry. Accessed March 27, 2024. https://www.nist.gov/organization-scientific-area-committees-forensic-science/osac-registry.

Organization of Scientific Area Committees (OSAC). OSAC Registry Approval Process. Accessed March 27, 2024. https://www.nist.gov/organization-scientific-area-committees-forensic-science/registry-approval-process.

Organization of Scientific Area Committees (OSAC). OSAC Registry Implementation: Frequently Asked Questions. Accessed March 27, 2024. https://www.nist.gov/osac/osac-registry-implementation-faqs.

Organization of Scientific Area Committees (OSAC). *Standard for Interpreting, Comparing and Reporting DNA Test Results Associated with Failed Controls and Contamination Events, Version 2.0. OSAC Proposed Standard 2020-S-0004*. May 19, 2023, 2021. https://www.nist.gov/system/files/documents/2021/06/01/OSAC%202020-S-0004_Standard_for_Interpreting_Comparing_and_Reporting_DNA_Test_Results_with_Failed_Controls_and_Contanimation%20FINAL%20OSAC%20PROPOSED.pdf.

Organization of Scientific Area Committees (OSAC). *Standard for Use of Serological Testing Methods Associated with Forensic Investigations, Version 2.0. OSAC Proposed Standard 2021-S-0028*. 2022. https://www.nist.gov/system/files/documents/2022/10/31/OSAC%202021-S-0028%20Standard%20Use%20of%20Serological%20Testing%20Methods_REGISTRY%20VERSION.pdf.

Organization of Scientific Area Committees (OSAC). *Standards for Determining Analytical and Stochastic Thresholds for Application to Forensic DNA Casework Using Electrophoresis Platforms, Version 1.0. OSAC Proposed Standard 2021-S-0003*. 2022. https://www.nist.gov/system/files/documents/2022/06/06/OSAC%202021-S-0003%20Standards%20for%20Determining%20Analytical%20and%20Stochastic%20Thresholds_OPEN%20COMMENT%20VERSION.pdf.

ORION. What Is Open Science? Accessed March 27, 2024. https://www.orion-openscience.eu/resources/open-science.

Orne MT. On the Social Psychology of the Psychological Experiment: With Particular Reference to Demand Characteristics and Their Implications. *American Psychologist*. 1962; 17(11):776-83. doi:10.1037/h0043424.

Osborne NKP, Taylor MC. Contextual Information Management: An Example of Independent-Checking in the Review of Laboratory-Based Bloodstain Pattern Analysis. *Science & Justice*. 2018; 58(3):226-31. doi:10.1016/j.scijus.2018.01.001.

Osborne NKP, Zajac R. An Imperfect Match? Crime‐Related Context Influences Fingerprint Decisions. *Applied Cognitive Psychology*. 2015; 30(1):126-34. doi:10.1002/acp.3180.

Park J, Feigenson N. Effects of a Visual Technology on Mock Juror Decision Making. *Applied Cognitive Psychology*. 2012; 27(2):235-46. doi:10.1002/acp.2900.

Parson W, Brandstätter A, Alonso A, Brandt N, Brinkmann B, Carracedo A, Corach D, Froment O, Furac I, Grzybowski T, Hedberg K, Keyser-Tracqui C, Kupiec T, Lutz-Bonengel S, Mevag B, Ploski R, Schmitter H, Schneider P, Syndercombe-Court D, Sorensen E, Thew H, Tully G, Scheithauer R. The EDNAP Mitochondrial DNA Population Database (EMPOP) Collaborative Exercises: Organisation, Results and Perspectives. *Forensic Science International*. 2004; 139(2-3):215-26. doi:10.1016/j.forsciint.2003.11.008.

Parsons HM. What Happened at Hawthorne?: New Evidence Suggests the Hawthorne Effect Resulted from Operant Reinforcement Contingencies. *Science*. 1974; 183(4128):922-32. doi:10.1126/science.183.4128.922.

Patterson RD. Auditory Warning Sounds in the Work Environment. *Philosophical Transactions of the Royal Society of London Series B: Biological Sciences*. 1990; 327(1241):485-92. doi:10.1098/rstb.1990.0091.

Percarpio KB, Watts BV, Weeks WB. The Effectiveness of Root Cause Analysis: What Does the Literature Tell Us? *The Joint Commission Journal on Quality and Patient Safety*. 2008; 34(7):391-8. doi:10.1016/S1553-7250(08)34049-5.

Perlin MW. Explaining the Likelihood Ratio in DNA Mixture Interpretation. Presented at: Proceedings of Promega's Twenty First International Symposium on Human Identification; 2010; https://www.promega.com/~/media/files/resources/conference%20proceedings/ishi%2021/oral%20presentations/perlin.pdf?la=en

Perlin MW. Inclusion Probability for DNA Mixtures Is a Subjective One-Sided Match Statistic Unrelated to Identification Information. *Journal of Pathology Informatics*. 2015; 6(1):59. doi:10.4103/2153-3539.168525.

Perlin MW. When Good DNA Goes Bad. *Journal of Forensic Research*. 2013; 04(01):S11. doi:10.4172/2157-7145.S11-003.

Perlin MW, Allan WP, Bracamontes JM, Danser KR, Legler MM. Reporting Exclusionary Results on Complex DNA Evidence, a Case Report Response to 'Uncertainty in Probabilistic Genotyping of Low Template DNA: A Case Study Comparing STRmix™ and Trueallele®' Software. 2023; doi:10.2139/ssrn.4449313.

Perlin MW, Dormer K, Hornyak J, Schiermeier-Wood L, Greenspoon S. TrueAllele® Casework on Virginia DNA Mixture Evidence: Computer and Manual Interpretation in 72 Reported Criminal Cases. *PloS One*. 2014; 9(3):e92837. doi:10.1371/journal.pone.0092837.

Perlin MW, Kadane JB, Cotton RW. Match Likelihood Ratio for Uncertain Genotypes. *Law, Probability and Risk*. 2009; 8(3):289-302. doi:10.2139/ssrn.1509435.

Perlin MW, Legler MM, Spencer CE, Smith JL, Allan WP, Belrose JL, Duceman BW. Validating TrueAllele® DNA Mixture Interpretation. *Journal of Forensic Sciences*. 2011; 56(6):1430-47. doi:10.1111/j.1556-4029.2011.01859.x.

Petersen D, Kovacs F. Phenolphthalein False-Positive Reactions from Legume Root Nodules. *Journal of Forensic Sciences*. 2014; 59(2):481-4. doi:10.1111/1556-4029.12352.

Peterson JL, Gaensslen RE. *Developing Criteria for Model External DNA Proficiency Testing, Final Report*. U.S. Department of Justice Office of Justice Programs. 2001. https://www.ojp.gov/library/publications/developing-criteria-model-external-dna-proficiency-testing-final-report.

Peterson JL, Leggett AS. The Evolution of Forensic Science: Progress Amid the Pitfalls. *Stetson Law Review*. 2006; 36:621-60.

Pierce ML, Cook LJ. Development and Implementation of an Effective Blind Proficiency Testing Program. *Journal of Forensic Sciences*. 2020; 65(3):809-14. doi:10.1111/1556-4029.14269.

President's Council of Advisors on Science and Technology (PCAST). *Report to the President: Forensic Science in Criminal Courts: Ensuring Scientific Validity of Feature-Comparison Methods*. 2016. https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/PCAST/pcast_forensic_science_report_final.pdf.

Prieto L, Haned H, Mosquera A, Crespillo M, Aleman M, Aler M, Alvarez F, Baeza-Richer C, Dominguez A, Doutremepuich C, Farfan MJ, Fenger-Gron M, Garcia-Ganivet JM, Gonzalez-Moya E, Hombreiro L, Lareu MV, Martinez-Jarreta B, Merigioli S, Milans Del Bosch P, Morling N, Munoz-Nieto M, Ortega-Gonzalez E, Pedrosa S, Perez R, Solis C, Yurrebaso I, Gill P. Euroforgen-NoE Collaborative Exercise on LRmix to Demonstrate Standardization of the Interpretation of Complex DNA Profiles. *Forensic Science International: Genetics*. 2014; 9:47-54. doi:10.1016/j.fsigen.2013.10.011.

Promega. Forensic-Grade Products for Human Identification: Preparing for ISO 18385 Requirements. Accessed March 27, 2024. https://www.promega.com/resources/profiles-in-dna/2014/forensic-grade-products-for-human-identification/#RelatedResourcesId-9273fe46-d63f-4c23-be66-e2fba4f5f333.

Puch-Solis R, Clayton T. Evidential Evaluation of DNA Profiles Using a Discrete Statistical Model Implemented in the DNA LiRa Software. *Forensic Science International: Genetics*. 2014; 11:220-8. doi:10.1016/j.fsigen.2014.04.005.

Pyrek KM. *Forensic Science Under Siege: The Challenges of Forensic Laboratories and the Medico-Legal Death Investigation System*. Elsevier / Academic Press: Amsterdam, Netherlands, 2007.

Quigley-McBride A, Dror IE, Roy T, Garrett BL, Kukucka J. A Practical Tool for Information Management in Forensic Decisions: Using Linear Sequential Unmasking-Expanded (LSU-

E) in Casework. *Forensic Science International: Synergy*. 2022; 4:100216. doi:10.1016/j.fsisyn.2022.100216.

R Core Team. The R Project for Statistical Computing. R Foundation for Statistical Computing. Accessed March 27, 2024. https://www.r-project.org/.

Rakay CA, Bregu J, Grgicak CM. Maximizing Allele Detection: Effects of Analytical Threshold and DNA Levels on Rates of Allele and Locus Drop-Out. *Forensic Science International: Genetics*. 2012; 6(6):723-8. doi:10.1016/j.fsigen.2012.06.012.

Reber R, Greifeneder R. Processing Fluency in Education: How Metacognitive Feelings Shape Learning, Belief Formation, and Affect. *Educational Psychologist*. 2016; 52(2):84-103. doi:10.1080/00461520.2016.1258173.

Reddy SC, Low CK, Lim YP, Low LL, Mardina F, Nursaleha MP. Computer Vision Syndrome: A Study of Knowledge and Practices in University Students. *Nepalese Journal of Ophthalmology*. 2013; 5(2):161-8. doi:10.3126/nepjoph.v5i2.8707.

Resnik DB. Employees as Research Participants: Ethical and Policy Issues. *IRB: Ethics & Human Research*. 2016; 38(4):11-16.

Ribeiro G, Likwornik H, Chin J. Visual Decision Aids: Improving Laypeople's Understanding of Forensic Science Evidence. *Journal of Applied Research in Memory and Cognition*. 2023; 12(2):230-40. doi:doi/10.1037/mac0000026.

Ribeiro G, Tangen JM, McKimmie BM. Beliefs About Error Rates and Human Judgment in Forensic Science. *Forensic Science International*. 2019; 297:138-47. doi:10.1016/j.forsciint.2019.01.034.

Ricardo & Barbosa. Using Human Factors, Human Error Prevention, and Mistake Proofing. Accessed March 27, 2024. https://www.ricardo-barbosa.com/using-human-factors-human-error-prevention-and-mistake-proofing/.

Ricci U, Carboni I, Torricelli F. False-Positive Results with Amylase Testing of Citrus Fruits. *Journal of Forensic Sciences*. 2014; 59(5):1410-2. doi:10.1111/1556-4029.12457.

Riman S, Iyer H, Vallone PM. Examining Performance and Likelihood Ratios for Two Likelihood Ratio Systems Using the PROVEDIt Dataset. *PloS One*. 2021; 16(9):e0256714. doi:10.1371/journal.pone.0256714.

Robertson B, Vignaux GA, Berger CEH. *Interpreting Evidence*. 2nd ed. Wiley & Sons: Chichester, UK, 2016.

Robertson CT, Kesselheim AS. *Blinding as a Solution to Bias: Strengthening Biomedical Science, Forensic Science, and Law*. Elsevier Academic Press: London, UK, 2016.

Robertson J, Kent K, Wilson-Wilde L. The Development of a Core Forensic Standards Framework for Australia. *Forensic Science Policy & Management: An International Journal*. 2014; 4(3-4):59-67. doi:10.1080/19409044.2013.858797.

Robino C, Ralf A, Pasino S, De Marchi MR, Ballantyne KN, Barbaro A, Bini C, Carnevali E, Casarino L, Di Gaetano C, Fabbri M, Ferri G, Giardina E, Gonzalez A, Matullo G, Nutini AL,

Onofri V, Piccinini A, Piglionica M, Ponzano E, Previdere C, Resta N, Scarnicci F, Seidita G, Sorcaburu-Cigliero S, Turrina S, Verzeletti A, Kayser M. Development of an Italian RM Y-STR Haplotype Database: Results of the 2013 GEFI Collaborative Exercise. *Forensic Science International: Genetics*. 2015; 15:56-63. doi:10.1016/j.fsigen.2014.10.008.

Robitaille D. *Root Cause Analysis: Basic Tools and Techniques*. Paton Professional: 2010.

Rodriguez L, Agtarap S, Boals A, Kearns NT, Bedford L. Making a Biased Jury Decision: Using the Steven Avery Murder Case to Investigate Potential Influences in Jury Decision-Making. *Psychology of Popular Media Culture*. 2019; 8(4):429-36. doi:10.1037/ppm0000192.

Rodriguez RG, Pattini AE. Neonatal Intensive Care Unit Lighting: Update and Recommendations. *Archivos Argentinos de Pediatria*. 2016; 114(4):361-7. doi:10.5546/aap.2016.eng.361.

Roelofsen P. Performance Loss in Open-Plan Offices Due to Noise by Speech. *Journal of Facilities Management*. 2008; 6(3):202-11. doi:10.1108/14725960810885970.

Ropero-Miller JD, Jones N. *Forensic Science State Commissions and Oversight Bodies—a 2022 Update*. Washington, DC. 2022. Forensic Technology Center of Excellence. doi: 10.4324/9780429326530. https://forensiccoe.org/private/6387e3c0cb5a7.

Royal Society. Research Culture. Accessed March 27, 2024. https://royalsociety.org/topics-policy/projects/research-culture/.

RTI International. Certified Forensic Manager. Accessed May 22, 2023. https://forensicrti.org/fmcp/cfm-overview/.

Russell L, Cooper S, Wivell R, Kerr Z, Taylor D, Buckleton J, Bright JA. A Guide to Results and Diagnostics within a STRmix™ Report. *WIREs Forensic Science*. 2019; 1(6):e1354. doi:10.1002/wfs2.1354.

Sacco DF, Bruton SV, Brown M. In Defense of the Questionable: Defining the Basis of Research Scientists' Engagement in Questionable Research Practices. *Journal of Empirical Research on Human Research Ethics*. 2018; 13(1):101-10. doi:10.1177/1556264617743834.

Saks MJ, Faigman DL. Failed Forensics: How Forensic Science Lost Its Way and How It Might Yet Find It. *Annual Review of Law and Social Science*. 2008; 4(1):149-71. doi:10.1146/annurev.lawsocsci.4.110707.172303.

Saks MJ, Koehler JJ. The Coming Paradigm Shift in Forensic Identification Science. *Science*. 2005; 309(5736):892-5. doi:10.1126/science.1111565.

Saks MJ, Koehler JJ. The Individualization Fallacy in Forensic Science Evidence. *Vanderbilt Law Review*. 2008;61:199-219. Accessed March 27, 2024. https://scholarship.law.vanderbilt.edu/vlr/vol61/iss1/4

Samie L, Champod C, Delémont S, Basset P, Hicks T, Castella V. Use of Bayesian Networks for the Investigation of the Nature of Biological Material in Casework. *Forensic Science International*. 2022; 331:111174. doi:10.1016/j.forsciint.2022.111174.

Sanders M, McCormick E. *Human Factors in Engineering and Design*. 7th ed. McGraw-Hill: New York, NY, 1993.

Sarabipour S. Research Culture: Virtual Conferences Raise Standards for Accessibility and Interactions. *Elife*. 2020; 9:e62668. doi:10.7554/eLife.62668.

Schilling J, Kluge A. Barriers to Organizational Learning: An Integration of Theory and Research. *International Journal of Management Reviews*. 2009; 11(3):337-60. doi:10.1111/j.1468-2370.2008.00242.x.

Schiro S, Elwood LS, Streed T, Kivisto AJ. Occupational Exposure to Traumatic Evidence and Posttraumatic Stress Symptoms in Forensic Science Professional: Prevalence and Patterns. *Journal of Forensic Sciences*. 2023; 68(4):1259-67. doi:10.1111/1556-4029.15292.

Schklar J, Diamond SS. Juror Reactions to DNA Evidence: Errors and Expectancies. *Law and Human Behavior*. 1999; 23(2):159-84. doi:10.1023/a:1022368801333.

Schlittmeier SJ, Liebl A. The Effects of Intelligible Irrelevant Background Speech in Offices – Cognitive Disturbance, Annoyance, and Solutions. *Facilities*. 2015; 33(1/2):61-75. doi:10.1108/f-05-2013-0036.

Schneider BA, Daneman M, Pichora-Fuller MK. Listening in Aging Adults: From Discourse Comprehension to Psychoacoustics. *Canadian Journal of Experimental Psychology*. 2002; 56(3):139-52. doi:10.1037/h0087392.

Schuerman C, Kalafut T, Buchanan C, Sutton J, Bright JA. Using the Nondonor Distribution to Improve Communication and Inform Decision Making for Low LRs from Minor Contributors in Mixed DNA Profiles. *Journal of Forensic Sciences*. 2020; 65(4):1072-84. doi:10.1111/1556-4029.14306.

Schwappach DLB, Taxis K, Pfeiffer Y. Oncology Nurses' Beliefs and Attitudes Towards the Double-Check of Chemotherapy Medications: A Cross-Sectional Survey Study. *BMC Health Services Research*. 2018; 18(1):123. doi:10.1186/s12913-018-2937-9.

Schweitzer NJ, Saks MJ. The CSI Effect: Popular Fiction About Forensic Science Affects Public Expectations About Real Forensic Science. *Jurimetrics: The Journal of Law, Science, and Technology*. 2007; 47(3):357-64.

Scientific Working Group on DNA Analysis Methods (SWGDAM). About Us. Accessed March 28, 2024. https://www.swgdam.org/about-us.

Scientific Working Group on DNA Analysis Methods (SWGDAM). *Contamination Prevention and Detection Guidelines for Forensic DNA Laboratories*. 2017. https://www.swgdam.org/_files/ugd/4344b0_c4d4dbba84f1400a98eaa2e48f2bf291.pdf.

Scientific Working Group on DNA Analysis Methods (SWGDAM). *The Guidance Document for the FBI Quality Assurance Standards for Forensic DNA Testing and DNA Databasing Laboratories*. 2020.

https://www.swgdam.org/_files/ugd/4344b0_2bce9398b6a640fdb626063469939151.pdf.

Scientific Working Group on DNA Analysis Methods (SWGDAM). *Guidelines for the Collection and Serological Examination of Biological Evidence*. 2015. https://www.swgdam.org/_files/ugd/4344b0_b3deba7a272b4b268d7f522840607410.pdf.

Scientific Working Group on DNA Analysis Methods (SWGDAM). *Recommendations of the SWGDAM Ad Hoc Working Group on Genotyping Results Reported as Likelihood Ratios*. 2018. https://www.swgdam.org/_files/ugd/4344b0_dd5221694d1448588dcd0937738c9e46.pdf.

Scientific Working Group on DNA Analysis Methods (SWGDAM). *Report on Y-Screening of Sexual Assault Evidence Kits (SAEKs)*. 2020. https://www.swgdam.org/_files/ugd/4344b0_e8334cb799704a1dabbd8d41f58b979d.pdf.

Scientific Working Group on DNA Analysis Methods (SWGDAM). SWGDAM Documents. Accessed March 27, 2024. https://www.swgdam.org/publications.

Scientific Working Group on DNA Analysis Methods (SWGDAM). *SWGDAM Guidelines for the Validation of Probabilistic Genotyping Systems*. 2015. https://www.swgdam.org/_files/ugd/4344b0_22776006b67c4a32a5ffc04fe3b56515.pdf.

Scientific Working Group on DNA Analysis Methods (SWGDAM). *SWGDAM Interpretation Guidelines for Autosomal STR Typing by Forensic DNA Testing Laboratories*. 2017. https://www.swgdam.org/_files/ugd/4344b0_3f94c9a6286048c3924c58e2c230e74e.pdf.

Scientific Working Group on DNA Analysis Methods (SWGDAM). *SWGDAM Training Guidelines*. 2020. https://www.swgdam.org/_files/ugd/4344b0_5e228328339443bfb197942f2d99f579.pdf.

Scientific Working Group on DNA Analysis Methods (SWGDAM). *Validation Guidelines for DNA Analysis Methods*. 2016. https://www.swgdam.org/_files/ugd/4344b0_813b241e8944497e99b9c45b163b76bd.pdf.

Seiberle I, Währer J, Kron S, Flury K, Girardin M, Schocker A, Schulz I. Collaborative Swab Performance Comparison and the Impact of Sampling Solution Volumes on DNA Recovery. *Forensic Science International: Genetics*. 2022; 59:102716. doi:10.1016/j.fsigen.2022.102716.

Semikhodskii A. Chapter 36: Logical Errors and Fallacies in DNA Evidence Interpretation. In: Dash HR, Shrivastava P, Lorente JA, eds. *Handbook of DNA Profiling*. Springer Nature: Singapore, 2022:799-820.

SERATEC. *PSA in Body Fluids: An Overview for Users of the SERATEC® PSA SEMIQUANT Tests*. Germany. 2011. https://www.seratec.com/docs/user_instructions/psa_in_body_fluids.

Sharfstein JM. Banishing "Stakeholders". *The Milbank Quarterly*. 2016; 94(3):476-9. doi:10.1111/1468-0009.12208.

Shelton DE. The 'CSI Effect': Does It Really Exist? Accessed March 27, 2024. https://nij.ojp.gov/topics/articles/csi-effect-does-it-really-exist.

Sijen T. Molecular Approaches for Forensic Cell Type Identification: On mRNA, miRNA, DNA Methylation and Microbial Markers. *Forensic Science International: Genetics*. 2015; 18:21-32. doi:10.1016/j.fsigen.2014.11.015.

Sinek S. *Start with Why: How Great Leaders Inspire Everyone to Take Action*. Portfolio: New York, NY, 2009. doi:10.1037/e515802011-001.

Sita J, Found B, Rogers DK. Forensic Handwriting Examiners' Expertise for Signature Comparison. *Journal of Forensic Sciences*. 2002; 47(5):1117-24. doi:10.1520/jfs15521j.

Sjerps M, Biesheuvel DB. The Interpretation of Conventional and 'Bayesian' Verbal Scales for Expressing Expert Opinion: A Small Experiment among Jurists. *International Journal of Speech, Language and the Law*. 1999; 6(2):214-27. doi:10.1558/ijsll.v6i2.214.

Slack DP. Trauma and Coping Mechanisms Exhibited by Forensic Science Practitioners: A Literature Review. *Forensic Science International: Synergy*. 2020; 2:310-6. doi:10.1016/j.fsisyn.2020.10.001.

Slooten K. The Comparison of DNA Mixture Profiles with Multiple Persons of Interest. *Forensic Science International: Genetics*. 2022; 56:102592. doi:10.1016/j.fsigen.2021.102592.

Slooten K. Likelihood Ratio Distributions and the (Ir)Relevance of Error Rates. *Forensic Science International: Genetics*. 2020; 44:102173. doi:10.1016/j.fsigen.2019.102173.

Slooten K. A Top-Down Approach to DNA Mixtures. *Forensic Science International: Genetics*. 2020; 46:102250. doi:10.1016/j.fsigen.2020.102250.

Slooten K, Caliebe A. Contributors Are a Nuisance (Parameter) for DNA Mixture Evidence Evaluation. *Forensic Science International: Genetics*. 2018; 37:116-25. doi:10.1016/j.fsigen.2018.05.004.

SNA International. *DC Department of Forensic Sciences Laboratory Assessment Report*. 2021. https://dfs.dc.gov/sites/default/files/dc/sites/dfs/publication/attachments/DFS%20Forensic%20Laboratory%20Assessment%20Report.pdf.

Sofronoff W. *Final Report: Commission of Inquiry into Forensic DNA Testing in Queensland*. 2022. https://www.health.qld.gov.au/__data/assets/pdf_file/0036/1196685/final-report-coi-dna-testing-qld-dec-2022.pdf.

Sommer P. Forensic Science Standards in Fast-Changing Environments. *Science & Justice*. 2010; 50(1):12-7. doi:10.1016/j.scijus.2009.11.006.

Speaker PJ. Process Improvement and the Efficient Frontier: Forecasting the Limits to Strategic Change across Crime Laboratory Areas of Investigation. *Forensic Science Policy & Management: An International Journal*. 2017; 8(3-4):109-27. doi:10.1080/19409044.2017.1387204.

Spellman BA, Eldridge H, Bieber P. Challenges to Reasoning in Forensic Science Decisions. *Forensic Science International: Synergy*. 2022; 4:100200. doi:10.1016/j.fsisyn.2021.100200.

Spengler JD, Chen QY. Indoor Air Quality Factors in Designing a Healthy Building. *Annual Review of Energy and the Environment*. 2000; 25(1):567-600. doi:10.1146/annurev.energy.25.1.567.

Spring Arbor University. Do Pets in the Workplace Improve Morale? Accessed March 27, 2024. https://online.arbor.edu/news/do-pets-workplace-improve-morale#:~:text=1%20Happier%2C%20more%20productive%20workers.%20Both%20pet%20owners,if%20they%20could%20bring%20their%20pet%20to%20work.

Srinivasan A, Kurey B. Creating a Culture of Quality. Harvard Business Review. Accessed March 27, 2024. https://hbr.org/2014/04/creating-a-culture-of-quality.

Staats BR, Gino F. Specialization and Variety in Repetitive Tasks: Evidence from a Japanese Bank. *Management Science*. 2012; 58(6):1141-59. doi:doi.org/10.1287/mnsc.1110.1482.

Standards Australia. *Forensic Analysis Reporting. AS 5388.4-2013* 2013. https://infostore.saiglobal.com/en-us/standards/as-5388-4-2013-120014_saig_as_as_251524/.

Staudenmayer N, Tyre M, Perlow L. Time to Change: Temporal Shifts as Enablers of Organizational Change. *Organization Science*. 2002; 13(5):583-97. doi:10.1287/orsc.13.5.583.7813.

Stelmaszczyk M. Relationship between Individual and Organizational Learning: Mediating Role of Team Learning. *Journal of Economics and Management*. 2016; 26:107-27. doi:10.22367/jem.2016.26.06.

Stoney DA. What Made Us Ever Think We Could Individualize Using Statistics? *Journal of the Forensic Science Society*. 1991; 31(2):197-9. doi:10.1016/s0015-7368(91)73138-1.

Streeting CA, Chaseling J, Krosch MN, Wright K. A Comparison of ABAcard® Hematrace® and RSID™-Blood Tests on Dried, Diluted Bloodstains Treated with Leucocrystal Violet or Luminol. *Australian Journal of Forensic Sciences*. 2022; 54(1):108-18. doi:10.1080/00450618.2020.1781256.

Stringfellow PF. *Evaluation of Large-Screen Display Use: Identifying Relevant Tasks and Associated Ergonomic Risks*. Doctoral dissertation. Clemson University; 2007.

https://www.proquest.com/openview/94064f0f29013091cb9e5663e135702a/1?pq-origsite=gscholar&cbl=18750.

STRmix™. DBLR™. Accessed March 27, 2024. https://strmix.com/dblr.

STRmix™. Home. Accessed March 27, 2024. https://strmix.com/.

STRmix™. Live Labs. Accessed April 24, 2024. https://strmix.com/strmix/live-strmix-labs/.

Summers K, Wyler H. Impact of In-Depth Information and Multimedia Presentation on Mock Jurors' Comprehension of Mitochondrial DNA Evidence. *Forensic Science International: Mind and Law*. 2022; 3:100072. doi:10.1016/j.fsiml.2022.100072.

Sundquist T, Bessetti J. Identifying and Preventing DNA Contamination in a DNA-Typing Laboratory. *Profiles in DNA*. 2005:11-13.

Sundstrom E, Town JP, Rice RW, Osborn DP, Brill M. Office Noise, Satisfaction, and Performance. *Environment and Behavior*. 2016; 26(2):195-222. doi:10.1177/001391659402600204.

Sweller J. Cognitive Load Theory, Learning Difficulty, and Instructional Design. *Learning and Instruction*. 1994; 4(4):295-312. doi:10.1016/0959-4752(94)90003-5.

Swiss Society of Legal Medicine. *Guidelines for Obtaining the Title "Forensic Geneticist SSLM"*. 2021. https://sgrm.ch/inhalte/Forensische-Genetik/Titelreglement_Forensische_Genetik_2021.pdf.

Taroni F, Aitken C, Garbolino P, Biedermann A. *Bayesian Networks and Probabilistic Inference in Forensic Science*. John Wiley & Sons, Ltd: West Sussex, England, 2006. doi:10.1002/0470091754.

Taroni F, Biedermann A. Uncertainty in Forensic Science: Experts, Probabilities and Bayes' Theorem. *Italian Journal of Applied Statistics*. 2015; 27(2):129-144.

Taroni F, Bozza S, Biedermann A, Garbolino P, Aitken C. *Data Analysis in Forensic Science: A Bayesian Decision Perspective*. John Wiley & Sons: West Sussex, UK, 2010. doi:10.1002/9780470665084.

Tassi P. Why 'Making a Murderer" Is Netflix's Most Significant Show Ever. *Forbes*. 2016. https://www.forbes.com/sites/insertcoin/2016/01/03/why-making-a-murderer-is-netflixs-most-significant-show-ever/?sh=163c6b9d326a

Taylor D, Balding D. How Can Courts Take into Account the Uncertainty in a Likelihood Ratio? *Forensic Science International: Genetics*. 2020; 48:102361. doi:10.1016/j.fsigen.2020.102361.

Taylor D, Bright JA, McGoven C, Hefford C, Kalafut T, Buckleton J. Validating Multiplexes for Use in Conjunction with Modern Interpretation Strategies. *Forensic Science International: Genetics*. 2016; 20:6-19. doi:10.1016/j.fsigen.2015.09.011.

Taylor D, Buckleton J, Bright JA. Factors Affecting Peak Height Variability for Short Tandem Repeat Data. *Forensic Science International: Genetics*. 2016; 21:126-33. doi:10.1016/j.fsigen.2015.12.009.

Taylor D, Buckleton J, Evett IW. Testing Likelihood Ratios Produced from Complex DNA Profiles. *Forensic Science International: Genetics*. 2015; 16:165-71. doi:10.1016/j.fsigen.2015.01.008.

Taylor D, Kitselaar M, Powers D. The Generalisability of Artificial Neural Networks Used to Classify Electrophoretic Data Produced under Different Conditions. *Forensic Science International: Genetics*. 2019; 38:181-84. doi:10.1016/j.fsigen.2018.10.019.

Taylor D, Kokshoorn B. *Forensic DNA Trace Evidence Interpretation: Activity Level Propositions and Likelihood Ratios*. CRC Press: Boca Raton, 2023. doi:10.4324/9781003273189.

Taylor D, Kokshoorn B, Biedermann A. Evaluation of Forensic Genetics Findings Given Activity Level Propositions: A Review. *Forensic Science International: Genetics*. 2018; 36:34-49. doi:10.1016/j.fsigen.2018.06.001.

Taylor D, Volgin L, Kokshoorn B, Champod C. The Importance of Considering Common Sources of Unknown DNA When Evaluating Findings Given Activity Level Propositions. *Forensic Science International: Genetics*. 2021; 53:102518. doi:10.1016/j.fsigen.2021.102518.

Taylor MC, Laber TL, Kish PE, Owens G, Osborne NKP. The Reliability of Pattern Classification in Bloodstain Pattern Analysis, Part 1: Bloodstain Patterns on Rigid Non-Absorbent Surfaces. *Journal of Forensic Sciences*. 2016; 61(4):922-7. doi:10.1111/1556-4029.13091.

Texas Administrative Code: 37. *§651.216. Disciplinary Action*. 2018. https://texreg.sos.state.tx.us/public/readtac$ext.TacPage?sl=T&app=9&p_dir=P&p_rloc=196522&p_tloc=&p_ploc=1&pg=7&p_tac=&ti=37&pt=15&ch=651&rl=216

Texas Administrative Code: 37. *§651.219. Code of Professional Responsibility*. 2020. http://txrules.elaws.us/rule/title37_chapter651_sec.651.219.

Texas Code of Criminal Procedure. *Chapter 38. Evidence in Criminal Actions. §38.01* 2021. https://statutes.capitol.texas.gov/docs/CR/htm/Cr.38.htm.

Texas Code of Criminal Procedure. *Chapter 39. Discovery. §39.14*. 2021. https://texas.public.law/statutes/tex._code_of_crim._proc._article_39.14.

Texas Courts. *Texas Forensic Science Commission Analyst and Technician Licensing Examination Basic Information Regarding Examination Content, Scoring and Syllabus*. https://www.txcourts.gov/media/1442019/licensingexamsyllabus_071918.pdf.

Texas Forensic Science Commission. Licensees. Accessed March 27, 2024. https://fsc.txcourts.gov/LicenseePublic.

Texas Forensic Science Commission. Texas Forensic Science Commission Forensic Analyst Licensing Program. Accessed March 27, 2024. https://www.txcourts.gov/fsc/licensing/.

Texas Government Code. *Chapter 411: Department of Public Safety of the State of Texas*. 2023. https://statutes.capitol.texas.gov/Docs/GV/htm/GV.411.htm.

Texas State Bill. *Texas State Bill No. 1287*. 2015. https://capitol.texas.gov/tlodocs/84R/billtext/pdf/SB01287F.pdf#navpanes=0.

The American Society of Crime Laboratory Directors (ASCLD). ASCLD Leadership Academy. Accessed March 23, 2024. https://www.ascld.org/ascld-leadership-academy/.

The American Society of Crime Laboratory Directors (ASCLD). *Executive Education Digest: A Leadership Development Resource for Forensic Science Laboratory Directors and Managers*. Vol. 5. 2016. https://www.ascld.org/wp-content/uploads/2016/04/2016-ASCLD-Executive-Education-Digest.pdf.

The American Society of Crime Laboratory Directors (ASCLD). *Trauma and Stress in the Field of Forensic Science*. 2019. https://www.ascld.org/wp-content/uploads/2019/02/Trauma-and-Stress-in-the-Field-of-Forensic-Science.pdf.

The American Society of Crime Laboratory Directors (ASCLD). Validation & Evaluation Repository. Accessed March 23, 2024. https://www.ascld.org/validation-evaluation-repository/?title=&keyword=&lab=&discipline=Biology/Serology&state=%5B619%5D.

Thompson WC. Are Juries Competent to Evaluate Statistical Evidence? *Law and Contemporary Problems*. 1989; 52(4):9-41. doi:10.2307/1191906.

Thompson WC. Painting the Target around the Matching Profile: The Texas Sharpshooter Fallacy in Forensic DNA Interpretation. *Law, Probability and Risk*. 2009; 8(3):257-76. doi:10.1093/lpr/mgp013.

Thompson WC. Subjective Interpretation, Laboratory Error and the Value of Forensic DNA Evidence: Three Case Studies. *Genetica*. 1995; 96(1-2):153-68. doi:10.1007/BF01441161.

Thompson WC. Uncertainty in Probabilistic Genotyping of Low Template DNA: A Case Study Comparing STRMix™ and TrueAllele®. *Journal of Forensic Sciences*. 2023; 68(3):1049-63. doi:10.1111/1556-4029.15225.

Thompson WC, Grady RH, Lai E, Stern HS. Perceived Strength of Forensic Scientists' Reporting Statements About Source Conclusions. *Law Probability & Risk*. 2018; 17(2):133-55. doi:10.1093/lpr/mgy012.

Thompson WC, Newman EJ. Lay Understanding of Forensic Statistics: Evaluation of Random Match Probabilities, Likelihood Ratios, and Verbal Equivalents. *Law and Human Behavior*. 2015; 39(4):332-49. doi:10.1037/lhb0000134.

Thompson WC, Schumann EL. Interpretation of Statistical Evidence in Criminal Trials: The Prosecutor's Fallacy and the Defense Attorney's Fallacy. *Law and Human Behavior*. 1987; 11(3):167-87. doi:10.1007/bf01044641.

Thompson WC, Scurich N. How Cross-Examination on Subjectivity and Bias Affects Jurors' Evaluations of Forensic Science Evidence. *Journal of Forensic Sciences*. 2019; 64(5):1379-88. doi:10.1111/1556-4029.14031.

Thompson WC, Taroni F, Aitken CG. How the Probability of a False Positive Affects the Value of DNA Evidence. *Journal of Forensic Sciences*. 2003; 48(1):47-54. doi:10.1520/JFS2001171.

Timken MD, Klein SB, Buoncristiani MR. Stochastic Sampling Effects in STR Typing: Implications for Analysis and Interpretation. *Forensic Science International: Genetics*. 2014; 11:195-204. doi:10.1016/j.fsigen.2014.03.015.

Tjin-A-Tsoi TBPM. *Trends, Challenges and Strategy in the Forensic Science Sector*. Netherlands Forensic Institute. 2013. https://www.nist.gov/system/files/documents/oles/trends-challenges-and-strategy-in-the-forensic-science-sector-march-2013-_tcm120-494231.pdf.

Toscanini U, Gusmão L, Álava Nárvaez MC, Alvarez JC, Baldassarri L, Barbaro A, Berardi G, Betancor Hernandez E, Camargo M, Carreras-Carbonell J, Castro J, Costa SC, Coufalova P, Dominguez V, Fagundes de Carvalho E, Ferreira STG, Furfuro S, Garcia O, Goios A, Gonzalez R, de la Vega AG, Gorostiza A, Hernandez A, Jimenez Moreno S, Lareu MV, Leon Almagro A, Marino M, Martinez G, Miozzo MC, Modesti NM, Onofri V, Pagano S, Pardo Arias B, Pedrosa S, Penacino GA, Pontes ML, Porto MJ, Puente-Prieto J, Perez RR, Ribeiro T, Rodriguez Cardozo B, Rodriguez Lesmes YM, Sala A, Santiago B, Saragoni VG, Serrano A, Streitenberger ER, Torres Morales MA, Vannelli Rey SA, Velazquez Miranda M, Whittle MR, Fernandez K, Salas A. Analysis of Uni and Bi-Parental Markers in Mixture Samples: Lessons from the 22nd GHEP-ISFG Intercomparison Exercise. *Forensic Science International: Genetics*. 2016; 25:63-72. doi:10.1016/j.fsigen.2016.07.010.

Tsai Y. Relationship between Organizational Culture, Leadership Behavior and Job Satisfaction. *BMC Health Services Research*. 2011; 11:98. doi:10.1186/1472-6963-11-98.

U.S. Equal Employment Opportunity Commission. Fact Sheet: Genetic Information Nondiscrimination Act. Accessed March 27, 2024. https://www.eeoc.gov/laws/guidance/fact-sheet-genetic-information-nondiscrimination-act.

Ulery BT, Hicklin RA, Buscaglia J, Roberts MA. Accuracy and Reliability of Forensic Latent Fingerprint Decisions. *Proceedings of the National Academy of Sciences of the United States of America*. 2011; 108(19):7733-8. doi:10.1073/pnas.1018707108.

United States Code Office of the Law Revision Counsel. *34 USC 40701: The Debbie Smith DNA Backlog Grant Program*. 2018. https://uscode.house.gov/view.xhtml?req=42+U.S.C.+%EF%BF%BD+14135&f=treesort&fq=true&num=0&hl=true&edition=prelim&granuleId=USC-prelim-title34-section40701.

United States Department of Health and Human Services. 45 CFR 46: Protection of Human Subjects. Accessed March 27, 2024. https://www.hhs.gov/ohrp/regulations-and-policy/regulations/45-cfr-46/index.html.

United States Department of Justice. *Code of Professional Responsibility for the Practice of Forensic Science* 2016. https://www.justice.gov/sites/default/files/code_of_professional_responsibility_for-the_practice_of_forensic_science_08242016.pdf.

United States Department of Justice. *Testimony Monitoring Framework*. 2020. https://www.justice.gov/media/1083376/dl.

United States Department of Justice. *Uniform Language for Testimony and Reports for Forensic Autosomal DNA Examinations Using Probabilistic Genotyping Systems*. 2022. https://www.justice.gov/olp/page/file/1095961/dl.

United States Government Accountability Office (GAO). *Science & Tech Spotlight: Probabilistic Genotyping Software*. Vol. GAO-19-707SP. 2019. https://www.gao.gov/assets/gao-19-707sp.pdf.

United States Supreme Court. *Brady v. Maryland, 373 U.S. 83*. 1963.

United States Supreme Court. *Daubert v. Merrell Dow Pharmaceuticals (92-102), 509 U.S. 579*. 1993.

United States Supreme Court. *Giglio v. United States, 405 U.S. 150* 1972.

Unkelbach C. The Learned Interpretation of Cognitive Fluency. *Psychological Science*. 2006; 17(4):339-45. doi:10.1111/j.1467-9280.2006.01708.x.

van Dalen HP, Henkens K. Intended and Unintended Consequences of a Publish‐or‐Perish Culture: A Worldwide Survey. *Journal of the American Society for Information Science and Technology*. 2012; 63(7):1282-93. doi:10.1002/asi.22636.

van den Berge M, Carracedo A, Gomes I, Graham EAM, Haas C, Hjort B, Hoff-Olsen P, Maronas O, Mevag B, Morling N, Niederstatter H, Parson W, Schneider PM, Court DS, Vidaki A, Sijen T. A Collaborative European Exercise on mRNA-Based Body Fluid/Skin Typing and Interpretation of DNA and RNA Results. *Forensic Science International: Genetics*. 2014; 10:40-8. doi:10.1016/j.fsigen.2014.01.006.

van Dyck C, Frese M, Baer M, Sonnentag S. Organizational Error Management Culture and Its Impact on Performance: A Two-Study Replication. *Journal of Applied Psychology*. 2005; 90(6):1228-40. doi:10.1037/0021-9010.90.6.1228.

van Oorschot RAH, Ballantyne KN, Mitchell RJ. Forensic Trace DNA: A Review. *Investigative Genetics*. 2010; 1(1):14. doi:10.1186/2041-2223-1-14.

van Oorschot RAH, Meakin GE, Kokshoorn B, Goray M, Szkuta B. DNA Transfer in Forensic Science: Recent Progress Towards Meeting Challenges. *Genes (Basel)*. 2021; 12(11):1766. doi:10.3390/genes12111766.

van Oorschot RAH, Szkuta B, Meakin GE, Kokshoorn B, Goray M. DNA Transfer in Forensic Science: A Review. *Forensic Science International: Genetics*. 2019; 38:140-66. doi:10.1016/j.fsigen.2018.10.014.

van Straalen EK, de Poot CJ, Malsch M, Elffers H. The Interpretation of Forensic Conclusions by Criminal Justice Professionals: The Same Evidence Interpreted Differently. *Forensic Science International*. 2020; 313:110331. doi:10.1016/j.forsciint.2020.110331.

Verdon TJ, Mitchell RJ, van Oorschot RA. Evaluating the Efficiency of DNA Extraction Methods from Different Substrates. *Forensic Science International: Genetics Supplement Series*. 2011; 3(1):e93-4. doi:10.1016/j.fsigss.2011.08.046.

Verdon TJ, Mitchell RJ, van Oorschot RAH. Swabs as DNA Collection Devices for Sampling Different Biological Materials from Different Substrates. *Journal of Forensic Sciences*. 2014; 59(4):1080-9. doi:10.1111/1556-4029.12427.

Vergeer P, van Es A, de Jongh A, Alberink I, Stoel R. Numerical Likelihood Ratios Outputted by LR Systems Are Often Based on Extrapolation: When to Stop Extrapolating? *Science & Justice*. 2016; 56(6):482-91. doi:10.1016/j.scijus.2016.06.003.

Vincent FHR. *Report: Inquiry into the Circumstances That Led to the Conviction of Mr Farah Abdulkadir Jama*. 2010. https://catalogue.nla.gov.au/catalog/4926898.

Virginia Commonwealth University (VCU) Department of Forensic Science. Forensic Firearms Identification Training. Accessed March 27, 2024. https://ocpe.vcu.edu/forensic-firearms-identification-training-certification-program/vcu.html.

Warr P. *Work, Happiness, and Unhappiness*. Lawrence Erlbaum Associates, Inc.: New Jersey, 2009.

West Virginia University. WVU Center for Executive Education Helping to Connect Forensic Science and Business. Lab Manager. Accessed March 27, 2024. https://www.labmanager.com/news/wvu-center-for-executive-education-helping-to-connect-forensic-science-and-business-4925.

White D, Kemp RI, Jenkins R, Matheson M, Burton AM. Passport Officers' Errors in Face Matching. *PloS One*. 2014; 9(8):e103510. doi:10.1371/journal.pone.0103510.

White House. Fact Sheet: Biden-Harris Administration Announces New Actions to Advance Open and Equitable Research. The White House,. Accessed March 27, 2024. https://www.whitehouse.gov/ostp/news-updates/2023/01/11/fact-sheet-biden-harris-administration-announces-new-actions-to-advance-open-and-equitable-research/.

Wick CW, León LS. From Ideas to Action: Creating a Learning Organization. *Human Resource Management*. 1995; 34(2):299-311. doi:10.1002/hrm.3930340207.

Wickens CD, Hollands JG, Banbury S, Parasuraman R. Attention in the Auditory Modality. *Engineering Psychology and Human Performance*. 4th ed. Psychology Press: Sussex, England, 2015.

Wild J, McKinnon A, Wilkins A, Browne H. Post-Traumatic Stress Disorder and Major Depression among Frontline Healthcare Staff Working During the COVID-19 Pandemic. *British Journal of Clinical Psychology*. 2022; 61(3):859-66. doi:10.1111/bjc.12340.

Williams PM. Techniques for Root Cause Analysis. *Baylor University Medical Center Proceedings*. 2001; 14(2):154-7. doi:10.1080/08998280.2001.11927753.

Willis S. Standards for the Formulation of Evaluative Forensic Science Expert Opinion Association of Forensic Science Providers. *Science & Justice*. 2010; 50(1):49. doi:10.1016/j.scijus.2009.11.004.

Wilmot EG, Edwardson CL, Achana FA, Davies MJ, Gorely T, Gray LJ, Khunti K, Yates T, Biddle SJ. Sedentary Time in Adults and the Association with Diabetes, Cardiovascular Disease and

Death: Systematic Review and Meta-Analysis. *Diabetologia*. 2012; 55(11):2895-905. doi:10.1007/s00125-012-2677-z.

Wilson-Wilde LM, Brandi J, Gutowski SJ. The Future of Forensic Science Standards. *Forensic Science International: Genetics Supplement Series*. 2011; 3(1):e333-4. doi:10.1016/j.fsigss.2011.09.029.

Woelfle M, Olliaro P, Todd MH. Open Science Is a Research Accelerator. *Nature Chemistry*. 2011; 3(10):745-8. doi:10.1038/nchem.1149.

World Health Organization. *Technical Series on Safer Primary Care: Human Factors*. Geneva. 2016:30. https://www.who.int/publications/i/item/9789241511612.

Worth K. Framed for Murder by His Own DNA. Accessed March 27, 2024. https://www.themarshallproject.org/2018/04/19/framed-for-murder-by-his-own-dna.

Yadav PK. Ethical Issues across Different Fields of Forensic Science. *Egyptian Journal of Forensic Sciences*. 2017; 7(1):10. doi:10.1186/s41935-017-0010-1.

Yang YJ, Prinz M, McKiernan H, Oldoni F. American Forensic DNA Practitioners' Opinion on Activity Level Evaluative Reporting. *Journal of Forensic Sciences*. 2022; 67(4):1357-69. doi:10.1111/1556-4029.15063.

Yapp R. Lee Iaccoca - The 10cs of Leadership. Accessed May 19, 2023. https://www.leadershipforces.com/lee-iacocca-leadership/.

Ypma RJF, Maaskant-van Wijk PA, Gill R, Sjerps M, van den Berge M. Calculating LRs for Presence of Body Fluids from mRNA Assay Data in Mixtures. *Forensic Science International: Genetics*. 2021; 52:102455. doi:10.1016/j.fsigen.2020.102455.

Zemlok R. A First Responder Spouse's Guide to Post Critical Incident Support. Accessed March 27, 2024. https://www.cordico.com/2020/08/21/a-first-responder-spouses-guide-to-post-critical-incident-support/.