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Review

Bloodstain Pattern Analysis (BPA): Validity, reliability, cognitive bias, and error rate

Itiel E. Dror

Cognitive Consultants International (CCI-HQ), United Kingdom

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ABSTRACT

Bloodstain Pattern Analysis (BPA) is a scientific endeavor as it is based on fluid dynamics, physics and mathematics which govern the creation of specific bloodstain patterns that are identified by BPA experts. It is used in police investigations and presented as forensic science evidence in court. However, examining bloodstain pattern analysis reveals some serious and severe concerns about its reliability, validity, vulnerability to bias, and error rates.

1. Introduction and background

Forensic science evidence is very significant in legal proceedings. It often plays a critical –and growing– role in convicting the guilty and exonerating the innocent. For many decades much of the forensic evidence has been generally viewed and accepted as impartial, objective and even 'infallible'. However, new insights and understandings about the true nature and limitations of forensic science evidence are changing that view. Wrongful convictions due to forensic evidence, research on forensic expert decision making, and several inquiries in the U.S. (as well as in the United Kingdom and other countries), all revealed that some forensic evidence domains are flawed or do not always produce reliable or valid results (e.g., [1–5]). Even the most established and scientifically grounded forensic domains (e.g., toxicology and DNA) are not infallible: they are susceptible to human error and bias (e.g., [6], for a review, see [7,8]).

The United States National Academy of Sciences (NAS) [1] conducted a detailed investigation into forensic science. It concluded that "with the exception of nuclear DNA analysis… no forensic method has been rigorously shown to have the capacity to consistently, and with a high degree of certainty, demonstrate a connection between evidence and a specific individual or source" (page 7 [1]). They also concluded that "a body of research is required to establish the limits and measures of performance and to address the impact of sources of variability and potential bias. Such research is sorely needed, but it seems to be lacking in most of the forensic disciplines that rely on subjective assessments of matching characteristics." The NAS report further states that "these disciplines need to develop rigorous protocols to guide these subjective interpretations and pursue equally rigorous research and evaluation programs" (page 8 [1]). Similar conclusions have been reached in other reports by U.S. governmental bodies (e.g., the President's Council of Advisors on Science and Technology (PCAST) [2]; the National Commission on Forensic Science [3]), as well as in other countries (e.g., the Shirley McKie Inquiry in the United Kingdom [4]).

Some forensic evidence that has been accepted and used to convict or exonerate suspects (e.g., hair analysis, bite marks, lead bullet analysis) has now been exposed as flawed. Research and actual criminal cases have revealed that even the most established and scientific forensic domains are susceptible to bias and error [4–6]. For example, knowing irrelevant contextual information (e.g., whether the suspect has a criminal record, the police theory, what other lines of evidence suggest, etc.) has a biasing impact on forensic examiners. Such biases have been observed in many forensic domains, including friction ridge examinations and comparisons [5] and DNA mixture interpretation [6] –for detailed reviews on cognitive bias in forensic decisions, see [7,8]. Indeed, examination of cases where people who have been wrongfully convicted and exonerated reveals that many included flawed or distorted forensic evidence [9].

Even without bias, it has been shown that forensic examiners are not consistent in their conclusions ("The Most Consistent Finding in Forensic Science is Inconsistency" [10]). Problems in repeatability and reproducibility are a significant concern. Not only can different forensic experts reach different conclusions, even in DNA (e.g., [11]), but the *same* expert looking at the *same* evidence at different times may reach

E-mail address: Itiel@cci-hq.com.

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different conclusions, even without bias. For example, the friction ridge Black Box study found that the same fingerprint expert, examining the same pair of fingerprints, reached different conclusions 10% of the time [12].

When it comes to Bloodstain Pattern Analysis (BPA), the focus of this Review, the issues described above are considerably magnified for several reasons:

1. BPA decisions often go beyond classification and involve reconstruction, hence they are also about *activities* rather than only about source. In most forensic domains, such as friction ridge and firearm comparisons, the forensic examiner only draws conclusions about the source of the evidence (e.g., is the suspect the source of the latent fingerprint found at the crime scene? Is the suspect's firearm the source of the cartridge case found at the crime scene? etc.). In contrast, in BPA not only is the bloodstain pattern identified and characterized, but BPA can draw conclusions about the activity level, that is, what happened? (e.g., the bloodstain was produced by –or 'consistent with'– a gunshot wound to the head).
2. BPA is subjective, and "the opinions of bloodstain pattern analysts are more subjective than scientific" (page 178 [1]).
3. BPA analysts, similar to CSI, are often present at the crime scene, and therefore exposed to irrelevant contextual information. Indeed, BPA often uses and relies on contextual information that is beyond the bloodstain pattern evidence itself (e.g., whether a knife or a firearm was found at the crime scene, what the police theory is, etc.).
4. BPA involves a multitude of factors and great complexity (details below).
5. BPA needs systematic scientific research. For example, "despite the frequency of clothing examinations in forensic laboratories around the world, the dynamics of bloodstain formation on textile surfaces remains under-researched" [13], and "in almost all experiments investigating bloodstains, the target is cleaned before impact. However, at a crime scene, a surface may have unknown coatings or contaminants which may be invisible to the eye" and which impact the bloodstain pattern [14]. Indeed, the lack of systematic scientific research into BPA is noted in a recent large study stating that BPA accuracy and reproducibility "have never been rigorously evaluated at a large scale" [15].
6. BPA currently lacks a proper and agreed consistent training for what is required to become a BPA examiner.

This Review focuses on four aspects of Bloodstain Pattern Analysis (BPA):

1. Validity. The theoretical and practical validity of BPA. That is, can BPA do what it claims, e.g., draw conclusions about the cause of a bloodstain pattern (a gun shot, knife stab, blunt instrument, blood dripping from a wound, a swipe transfer from another bloody object, etc.), or even the source from where the bloodstain pattern originated (distance, trajectory, location, etc.)?
2. Reliability. The reproducibility, or the repeatability, of BPA. Will BPA produce consistent results, or will different examiners reach different conclusions when examining the same bloodstain pattern?
3. Bias. If, and to what extent, is BPA impacted by bias? That is, how objective is BPA and how much (if at all) is it susceptible to the influence of bias?
4. Error rate. Do BPA analysts incorrectly classify and interpret the bloodstains they examine? And if so, how often?

2. Validity

In theory, BPA should be objective and scientific. It is supposed to be underpinned by the laws of physics, specifically fluid dynamics. For example, if knife X, stabs the body with force Y, at location Z, the resulting bloodstain can be fully and accurately calculated based on the laws of physics. Hence, at a first and a superficial glance, BPA is a scientifically valid forensic domain as it is based on fluid dynamics.

However, a closer look at the theoretical and practical validity of BPA gives a very different picture. Generally speaking, a valid method is one that returns an accurate result routinely. Here I want to distinguish between whether a method in *theory* can return an accurate result routinely, and whether a method can in *practice* (given the pragmatic capabilities available, how it is used and applied in practice) return an accurate result routinely. A domain may have theoretical validity, but because of limited or missing technology, necessary computations, and other pragmatic issues, does not have practical validity. Thus, theoretical validity refers to the validity regardless of any pragmatic and practical considerations, i.e., when everything is known and possible, are there validity issues. In contrast, practical validity includes the pragmatic and practical issues, i.e., even if there is theoretical validity, practical issues and obstacles may prevent reaching valid conclusions.

The critical point is that although BPA has been used in criminal investigations for over 100 years [16], "its use and acceptance occurred without rigorous validation" (page 922 [17]; see also [1,15]). In drawing attention to BPA, this article seeks to examine BPA's validity, in theory (whether it can deliver what it promises, in theory), as well as in practice (whether it can deliver what it promises, in practice). Much of the validity issue in the literature has focused on classification, neglecting reconstruction validity which is used in court.

Theoretical Validity. Bloodstain pattern analysis is complex because there are many factors and causes that result in a bloodstain pattern. There are a multitude of potential causes (knife stab, blunt instrument, gunshot, coughing blood, etc.) that create a bloodstain pattern, as well as many other factors relating to the force and location that an object impacted the body. Also, gravitational force, drag, viscosity, etc., are at play, and it is not clear whether or not (and how) they can be applied to BPA.

Furthermore, there are other factors that mediate the resulting bloodstain pattern which add more complexity. For example, the surface on which the bloodstain pattern is deposited (the material and texture, and their characteristics, e.g., the absorbency of different types and textures of walls, carpets, clothing, etc.) impacts the bloodstain pattern. Bloodstain patterns that are formed on wallpapered walls, for example, will differ depending on the specific type of wallpaper, e.g., "bloodstains become highly distorted or deformed across the Woodchip and Anaglypta wallpapers" [18].

In addition, the surrounding environmental conditions (e.g., temperature, air flow, etc.), as well as the angle of impact (both of the angle in which the causing object hits the body and the angle at which the blood hits a surface), are a number of additional important factors that play a role in the formation and appearance of the bloodstain pattern [16]. Even one source of the impact (e.g., a knife or a gunshot) is insufficient because knives come in different shapes and sizes, can be serrated or not, and guns come in a huge variety, and even one gun can have a variety of ammunition types, etc.

To make matters even more complicated, there are many other factors, complexities, and uncertainties that determine the way bloodstain patterns are formed and deposited on a surface. For instance, the trajectory of blood exiting the body may have a curved path or a relatively straight path trajectory. Also, the rate at which blood exits the body depends on which blood vessels were damaged, the vessel characteristics and location, how the vessels were damaged, etc. For example, whether the bleeding is from a vein versus an artery –that is, blood going from the body to the heart versus blood from the heart going to the body– the former bleeding is steady, whereas the latter bleeding comes out in spurts. The variations in the blood may be further impacted and changed if the person was using drugs, such as anticoagulants (i.e., anticlotting agents), or other substances that impact the coagulation of blood. Indeed, there are multiple parameters existing within the human body that impact the resulting bloodstain pattern. Furthermore, the lack of realistic models to simulate human tissue, in particular microvascular structures is also an issue [19].

Beyond the human body, there are many additional factors and complexities involved in BPA (see foundational BPA textbooks, e.g., [16,20]. For instance, "under the same impact conditions, the bloodstain size might differ if the target were glass as opposed to polycarbonate" (page 189 [14]). This is especially problematic as "in almost all experiments investigating bloodstains, the target is cleaned before impact. However, at a crime scene, a surface may have unknown coatings or contaminants which may be invisible to the eye" (page 189 [14]). Indeed, the effects of such microscopic coatings on bloodstain size and shape have been demonstrated to be potentially "dramatic." For example, fingerprint residue reduced stain size by 35 %, and vegetable oil reduced stain size by almost half (page 197 [14]).

The list of parameters and factors impacting BPA is long and poorly understood. In the words of the NAS Report: "many sources of variability arise with the production of bloodstain patterns, and their interpretation is not nearly as straightforward as the process implies" (page 177 [1]), and "the uncertainties associated with bloodstain pattern analysis are enormous" (page 179 [1]). Many factors, causes, and parameters determine the pattern of the bloodstain, rendering the validity of the practice extremely difficult to establish. Only recently, peer-reviewed fluid dynamic studies have started to uncover the complex physics underlying BPA (21).

The theoretical validity problem does not go away even when all relevant parameters are known and can be calculated to the exact resulting specific bloodstain pattern. Even then, with the parameters fully known, we are still faced with an insurmountable theoretical problem because "different bloodletting mechanisms can give rise to bloodstain patterns that possess similar or indistinguishable characteristics" (page 922 [17]). For example, a bloodstain pattern caused by the expiration of air can have similar characteristics to a pattern caused by blunt force trauma [20]. Thus, there is a serious issue even when BPA experts just identify, classify, and attribute a bloodstain pattern.

The fact that a specific bloodstain pattern can be created in different ways seriously undermines the theoretical validity of BPA. Research on BPA may have demonstrated that a certain specific set of causes and circumstances results in a certain and specific bloodstain pattern. However, the research has not (yet) made a good case that *other* causes and circumstances cannot *also* result in a comparable bloodstain pattern. That is, many different conditions can lead to a similarly appearing bloodstain pattern. Hence, testimony that a bloodstain pattern was created by, or is "consistent with" X, means very little when there may be many (unknown number) of *other* causes and circumstances that can create the same specific bloodstain pattern (see Fig. 1 versus Fig. 2).

The issue of BPA's validity is not limited to its theoretical validity, as explained above. There are also issues with its practical validity, which are discussed next.

*Practical Validity***.** Although BPA is theoretically based on sound science (physics), the number of variables involved and the many possible ways in which they interact give rise to an issue of computational complexity. For example, fluid dynamics often requires that nonlinearity is present in the equations (see, e.g., Navier–Stokes equations), which involve complex nonlinear and dissipative terms.

The level of mathematical education, knowledge, and ability needed to compute these parameters and their interactions is a problem because rarely do BPA experts possess advanced degrees in mathematics or physics (or even an undergraduate degree in a natural science). Hence, most BPA examiners do not have the background and knowledge to compute the necessary mathematics. Indeed, "nonscientist practitioners do not have an adequate scientific background to properly interpret results derived from natural law" (page 170 [19]).

Even with the needed education and knowledge, the computational complexity involved in calculating the underlying math presents an enormous practical validity issue. First, the scientific community has yet to fully understand all the interactive and interdependent variables needed to adequately calculate the fluid dynamics of bloodstains. Second, the computational complexity in their calculation is very hard to carry out in practice. Thus, in addition to the issues discussed above with BPA's theoretical validity, practical validity is another obstacle since many analysts cannot realistically carry out the intense computations typically required to understand/predict fluid dynamics.

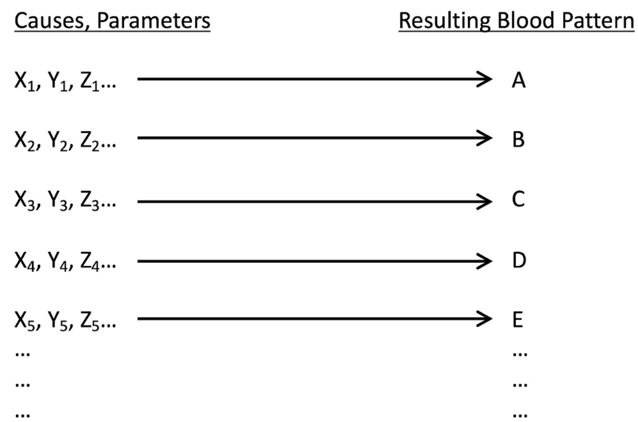

Fig. 1. A one-to-one relationship between causes and parameters that give rise and result in a bloodstain pattern. On the left are the specific circumstances (for example, the cause (e.g., a knife of a specific shape and size, or a specific caliber gun with ammunition of a certain size and make), the part of the body injured, the force of impact, the angle of impact, and the nature of the surface on which the bloodstain pattern was deposited, etc.). An endless number of combinations of possible circumstances exist (in the illustration, only 5 are presented, with only three parameters, X, Y, and Z). On the right side, there is a resulting bloodstain pattern for each of these specific combinations of circumstances. If there is a one-to-one relationship (as illustrated by the arrows), then BPA consists of 'going backward', e.g., if we see bloodstain pattern C, we know it was caused by circumstances X3, Y3, and Z3.

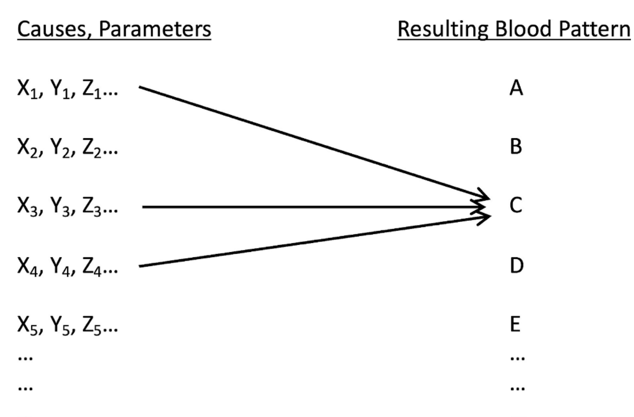

Fig. 2. Many different causes and parameters can cause the same bloodstain pattern. As in Fig. 1, on the left are the specific circumstances, and on the right side is the resulting bloodstain pattern. If there is a many-to-one relationship (as illustrated by the arrows), then BPA cannot 'go backward' because bloodstain pattern C could have been created by circumstances X1, Y1, and Z1, or X3, Y3, and Z3, or even X4, Y4, and Z4. The figure is an illustration, of course, given the infinite number of possible circumstances, there can be many different causes which result in a comparable bloodstain pattern. Therefore, unless analysts can identify all the alternative possible causes, or the likelihood of a certain cause, any conclusion that a bloodstain pattern is consistent with a certain set of circumstances is uninformative and can actually be misleading.

Beyond the needed knowledge and background education for being able to compute the necessary mathematics, the current requirements for basic BPA training of the International Association of Bloodstain Pattern Analysis (IABPA) are minimal. The requirement is for only 40 hours, a week of training (see recommended basic BPA course guidelines [22]). This basic requirement is sometimes supplemented by rigorous mentorship and advanced courses in fluid dynamics, physics, bias training, and crime scene reconstruction, but such further education and training is not mandatory. Furthermore, without an accepted and defined methodology, "the criteria for these decisions have not been clearly defined in the BPA discipline" [15] (see more below), thus there is an issue what BPA training can provide.

The issue of computational complexity and mathematics involved in Navier–Stokes equations and their complex nonlinear and dissipative terms that underpin much of fluid dynamics is not often used or required in the day-to-day work of BPA. Rather BPA is more often an observational pattern classification task, comparing the features observed within a given blood stain or pattern with mental models stored in the practitioner's head. Thus, in practice, most often there is little measurement and quantification beyond maybe the relatively simple trigonometry calculations as per the area of origin. This leads to two issues with the practical validity.

First, all the theoretical validity framework that BPA is objective and scientific, based on fluid dynamics, etc., is actually wrong and misleading. BPA is actually (as practiced, see paragraph above) mainly a feature comparison based forensic domain, such as fingerprinting and firearms. As such, it is open to all the issues and weaknesses of such subjective domains and cannot be understood or presented as a more objective forensic domain because it is based on physics.

Second, given that much of the work of BPA is actually a subjective feature comparison based forensic domain, there is a lack of accepted and defined methodology (see, e.g., [15]). For example, there are no definitive lists of what features should (or should not) be present in each stain type. Indeed, there is a "lack of a widely accepted and well-defined methodology and ambiguity often associated with examining bloodstain patterns" [23].

Furthermore, there is very little empirical research on what each stain type looks like on different surfaces; and very little research on the impact of the myriad of variables (e.g. location on body of wound; amount of force; specific weapon; receiving surface; environmental conditions; movement of target etc.). As the reliability and error rates sections show (see below), this lack of knowledge has major implications on the ability for practitioners to correctly and reliably classify stains.

On the positive note, there are now efforts to develop a more scientific quantitative approach to BPA. However, there is a long way to go and it is more work in progress rather than established scientific practices (e.g., [21,23–26]. Furthermore, there is a serious issue that even when good procedures and standards are in place (e.g., OSAC, see below), whether BPA examiners doing casework actually use and follow these standards.

3. Reliability

Reliability –as it is used in science and in this report (not the way lawyers often use it in the legal settings)– refers to the consistency of results [10]. That is, when a BPA expert (or any other expert) reaches a conclusion, will their results be replicated, are they repeatable and reproducible? Will another expert (or even the same expert) reach the same conclusion when examining the same evidence? Hence, reliability pertains to consistency in conclusions.

Reliability is fundamental and even more basic than validity. Consider a weighing scale: If the scale shows that I am 170 pounds, I get off and then back on the scale again, but now it shows that I am 160 pounds, and when I get off and on again it shows that I am now 180 pounds, then the scale is useless. Its results are not reliable because each time we get different results. If the weighing scale is reliable, i.e., it consistently shows the same weight each time, only then can one ask and consider whether it gives an accurate result (i.e., the scale's validity). But without consistency (i.e., reliability), then one cannot consider validity (see details in [10]). When discussing reliability, one must distinguish it from systematic bias [27], which is discussed in the next section.

Research has shown that even forensic experts can lack reliability, i.e., that different experts can reach different conclusions when examining the same evidence (e.g., [6,11]). Furthermore, even the *same* expert may reach a different conclusion when they examine the *same* evidence. For example, the same fingerprint expert, examining the same pair of prints will reach different conclusions 10% of the time [12].

While low reliability may be tolerable when the decision is which car to buy, it is a major and concerning issue if an expert evaluation sends someone to prison (or to freedom), while the evaluation of another competent expert would have had the opposite result (or, even worse, when the same expert may have reached a different conclusion about the same evidence at a different time).

What do we know about BPA's reliability? Are BPA experts consistent and their decisions repeatable and reproducible? Or do they disagree with each other, and will they reach a different conclusion about the same bloodstain at different times? Researchers have only begun to examine these questions. The results support the NAS' conclusion that "the opinions of bloodstain pattern analysts are more subjective than scientific".

The level of consistency, the lack of reliability (between and within examiners), is a function of the case. Thus, "it is important to note that such inconsistencies are much more pronounced in the more difficult cases" [10]. That is, lack of reliability is more prevalent in the more difficult and complex cases. In the simpler and easier cases, there will be more consistency in decisions. However, making decisions in simple cases does not require much expertise, often novices can perform the task –expertise comes into play in those more difficult and challenging cases.

A larger study specifically in BPA found problems with the reliability ("Accuracy and Reproducibility of Conclusions by Forensic Bloodstain Pattern Analysts" [15]). The study observed that "consensus was limited." Indeed, the researchers found that their "results show that conclusions by BPA analysts … often contradicted other analysts." Thus, BPA's reliability has shown that experts are not consistent in their conclusions when examining the same identical bloodstain patterns.

4. Cognitive Bias

The above discussion on the validity and reliability of BPA did not include the impact of cognitive bias in BPA decision making. Cognitive bias is recognized as affecting human decisions, and it arises from the human brain's cognitive architecture. Scientific research into human cognition is well established by decades of rigorous behavioral experimentation, studies of the human brain, and computer simulations. All of these converge to provide scientific insights into perception and judgment (e.g., [28]).

Cognitive bias is widely spread across people and has many manifestations [29]. Before going any further, it is important to clearly state and emphasize that *cognitive* bias differs from the everyday usage of the term "bias" (an intentional discriminatory bias, such as sexism, racism, or antisemitism). Cognitive bias is unintentional implicit bias that impacts even hard working, competent, and dedicated experts. Hence, I am not accusing (or even suggesting) that any forensic examiner is intentionally biased. The bias at issue here is *cognitive* bias that arises from how the brain processes information and is not the fault of the examiner (see 'bias fallacies' #1, Ethical Issues, and #2, Bad Apples, in [30]).

It is essential to distinguish between *bottom-up* processes that are data-driven versus *top-down* processes that are guided and driven by factors that are unrelated to the actual data provided by the external world. The top-down influences include, among other things, contextual information, expectation, what we already know (or think we know), hope, motivation, ideology, beliefs, training, and state of mind. The existence and power of such top-down processes in shaping judgments and decision making has been demonstrated time and again in a variety of studies using various scientific methodologies – all confirming the power of top-down information processing.

Top-down contextual processing can interfere and contaminate our judgement and decision making. These biases and distortions arise from a long and well-studied list of cognitive and psychological phenomena (for a review, see [29,31]). These phenomena, such as confirmation bias, cognitive dissonance, self-fulfilling prophecies, motivated reasoning, hindsight bias, decision momentum, mindset, and others, all impact forensic experts. These established cognitive and psychological phenomena all cause people to lose objectivity. It is important to emphasize that these are implicit cognitive biases, not intentional, and without awareness.

Bottom-up cognitive processes consider the evidence itself, on its own merit, without external influences. Loss of objectivity is greater when we do not acknowledge and protect ourselves from our own biases (e.g., by limiting our access and exposure to unnecessary and task-irrelevant contextual information) and thus do not examine the evidence and data by itself. When we engage in top-down processes, we examine data under external influences. In top-down contextual processes, we unavoidably and unconsciously perceive and judge the data differently than in bottom-up processes.

Forensic confirmation bias is "the class of effects through which an individual's pre-existing beliefs, expectations, motives, and situational context influence the collection, perception, and interpretation of evidence during the course of a criminal case" [32]. Indeed, it has been shown that experts are susceptible to top-down contextual interferences and that these can (and have) caused erroneous judgment and misleading biased evidence in casework and court (see, e.g., [5], and bias fallacy #3, 'Expert Immunity', in [30]).

With such influences, we as humans interact subjectively and in a biased fashion with the evidence. This is manifested in a variety of ways, for example:

- Our examination of the evidence is motivated and more likely to notice and focus on parts of the evidence that validate and confirm our beliefs and pre-existing views. Thus, the way we search and allocate attention to the evidence is selective and biased.
- Confirming evidence is emphasized and weighted highly.
- Perhaps most notably, we accept confirming evidence, even if it is not reliable and is from questionable sources.
- We tend to avoid and not notice evidence that conflicts and contradicts with what we expect to find.
- Contradictory evidence that is noticed is often ignored.
- Evidence that does not fit and cannot easily be ignored, is dismissed and explained away.
- Contradictory evidence is weighted low.

These and other manifestations of bias are well researched and documented by many scientific studies (e.g., [33–35]).

Are experts immune from influences and biases? Are biases limited to impacting incompetent experts? Can experts overcome bias by mere willpower? The short answer to these questions is 'no'. Experts across domains are susceptible to such biases, including, specifically, forensic science experts [36–39]. Indeed, erroneous decisions because of bias have led to incorrect diagnoses and accidents in the medical, aviation and military domains, as well as in forensic science and the criminal justice system (e.g., [5,38]).

In short, cognitive bias and top-down processing affects everyone, and forensic experts are not an exception. In fact, forensic expert analysis has been shown to be affected by irrelevant case information, the expectations of the party requesting assistance, or other information unrelated to the forensic analysis they are asked to perform.

There are many different sources of cognitive biases. Broadly speaking, there are eight sources of cognitive bias which fall into three categories (see Fig. 3). The first category of sources of bias (A) relate to the specific case before the forensic expert. Thus, 'Category A' biases are generated by the case being investigated. These may include contextual facts that are not relevant to the analysis, but nevertheless impact and bias the decisions, such as the past criminal conviction of the suspect or the police theory of the case (see details in [30]). In contrast, the next

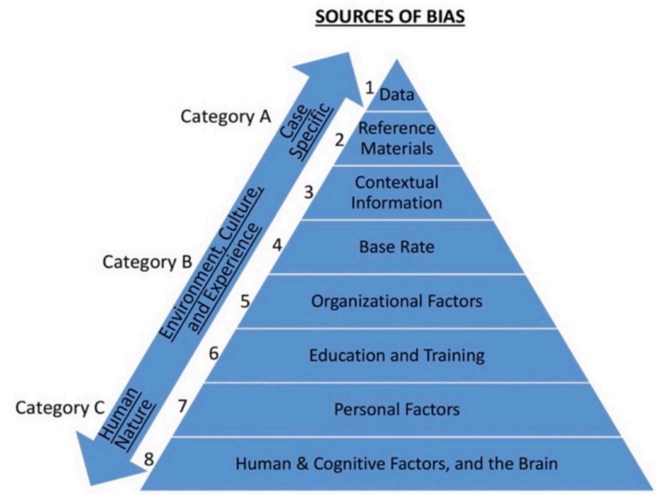

Fig. 3. Eight sources of bias that can contaminate data collection, analysis and conclusions, even by experts. They are organized in a taxonomy within three categories: starting off at the top with sources relating to the specific case (Category A), moving down to sources that relate to the specific person doing the analysis (Category B), and at the very bottom sources that relate to human nature (Category C). Taken from [30].

category (B) of sources of bias, have nothing to do with the specific case at hand, but relate to the specific person doing the analysis. The expert's ideologies, beliefs, past experiences, organizational culture, training, and a whole set of factors relating to them impacts and biases their analysis. The last category (C), is not about the specific case at hand, nor about the specific person doing the analysis, but has to do with human nature –how the brain processes information and cognitive architecture– thus not dependent on the case at hand or who is doing the analysis.

A domain such as BPA is a fertile ground for cognitive bias and it is within the *bias danger zone* because of its overall subjective nature. Although some elements in BPA are more objective, the overall conclusions are subjective since some elements are subjective (the strength of the chain is determined by the weakest link). Other factors (such as organizational factors, see Level 5 in Fig. 3) thus have greater leeway to bias and impact it, e.g. "many bloodstain pattern analysis cases are prosecution driven or defense driven, with targeted requests that can lead to context bias" (page 178 [1]).

BPA's lack of a methodology that specifically addresses the issue of bias further makes it vulnerable to the distorting influences of bias. It is important to note that there is a positive move to adopt such bias countering measures –[40] details below– but this has not yet to be adopted and implemented as part of BPA standard procedures and impact how casework is actually carried out. The problems with reliability (see above) are a testimony to, and a reflection of, these problems. Indeed, the research into BPA not only shows issues with reliability, but also (on top of the other issues) a serious problem regarding cognitive bias.

Several pioneering studies published in 2016 documented the distorting effects of confirmation bias and contextual influences on BPA analysts [13,17,39]. In the first of those studies the researchers concluded that "our findings clearly demonstrate that contextual information can influence decision-making…" and that, "the bloodstain interpretation process is vulnerable to contextual bias" (pages 126 and 127 [39]).

Examining the bloodstain pattern and making an initial decision before exposure to the contextual information minimizes the impact of contextual information (see Linear Sequential Unmasking (LSU) [42]). In casework, almost always analysts are provided with contextual information before they have their own initial impression about the BPA

–often the context is provided before they even see the bloodstain. A positive move in the right direction can be seen in the recent (May 2023) OSAC Proposed Standard (2022-S-0030) for Methodology in Bloodstain Pattern Analysis [40]. It states: "Analysts will be exposed to various sources and types of information throughout their analysis which may be task-relevant or task-irrelevant. When considering how this information can influence their decision-making, they shall consider and document the potential for cognitive bias. Where possible, this methodology should follow linear sequential unmasking – expanded. The analyst shall access information in the following order prescribed by the methodology. If information is accessed out of order, it shall be documented and explained" (page 2).

It further mandates that "to limit the role of contextual bias and improve bloodstain pattern analysis decision making, a linear sequential unmasking-expanded approach is incorporated in this methodology to manage exposure to task-irrelevant data by optimizing the order of information processing" (page 1). Furthermore, the International Association of Bloodstain Pattern Analysis (IABPA), has shown openness and initiative for dealing with bias and establishing proper methodology. All encouraging moves to tackle the issues of bias in BPA.

In a study that used more than 400 bloodstain patterns to examine the impact of cognitive bias in BPA ([17] more details are provided further below), it was found that when experts in BPA were exposed to contextual information, that information could bias examiners to make an incorrect analysis about the actual evidence. When provided with misleading contextual information, the "analysts were more likely to make an incorrect classification than when the context was neutral, with the overall error rate increasing to 20 %" (page 926 [17]). These studies were further replicated in another study [13], where similar biasing effects were documented, concluding that "bloodstain pattern classifications on fabric surfaces are vulnerable to contextual bias" (page 5 [13]).

Studies have repeatedly "produced evidence that analysts consider contextual information when classifying bloodstain patterns and that this information can influence accuracy. These findings may be evidence for confirmation bias where analysts interpreted the pattern in line with the expectation created by the contextual cues" (page 927 [17]; see also [41]). The findings clearly suggest that until procedures for the safer use of contextual information are created and validated "analysts would be wise to restrict access to contextual information to help minimize the potential for bias in their decision-making" (page 5 [13]).

There is a critical question about what information is irrelevant to BPA and how to use the relevant information –a fundamental question that must be addressed. Although BPA has yet to fully consider and agree upon these fundamental questions [43], other domains have started to make such determinations –see for example the Proposed Standard OSAC 2023-S-0026 about Task-Relevant Information in Friction Ridge Examination [44]. Although coming up with such a list is complex in an area such as BPA, some contextual information is clearly irrelevant, such as the race and the past criminal convictions of the suspect.

The fact that an analyst's knowledge of contextual information can create bias and result in incorrect analysis is a major problem for BPA as forensic evidence. In practice BPA analysts are consistently exposed to task irrelevant contextual information. As discussed above, exposure to task irrelevant contextual information makes BPA experts further susceptible to cognitive bias. Indeed, such contextual information can even override the actual evidence [45]. Adding the propensity for cognitive bias to BPA's subjective nature and the lack of an agreed and mandatory scientific methodology in general [43], and specifically for minimizing the bias in BPA, makes BPA very vulnerable to the impact of bias.

5. Error Rate

Assessing the error rate is critically important to scientific endeavours, but it is a complex task, especially in forensic science (see "The Error in Error Rate: Why error rates are so needed, yet so elusive" [46]). It is important to note that under 'errors' I do not include 'mistakes' that can occur due to negligence, incompetence, lack of training, not following the method, etc. There are several issues and challenges pertaining to establishing an error rate. A challenge in error rate determination is which test items to use. For example, easy test items yield a lower error rate, whereas difficult test items yield a higher error rate. Thus, which test items are used in error rate studies plays a significant role in the resulting error rate.

Another issue in establishing an error rate is how to score and calculate the error rate. For example, the scoring of 'inconclusive' decisions, which is when examiners decide not to decide [47], can dramatically affect the calculation of error rates. A further challenge to studying error rates is the ecological validity of the study, e.g., people's performance is different when they know they are being tested or monitored than it is when they do casework.

There are many other issues and complexities with attempting to determine an error rate, all of which produce inaccurate findings, often with a misleading underestimation of error rates as they occur in real cases –for an extensive and detailed review of the complexities inherent to the assessment of error rates, see [46].

BPA has been used in courts for over 100 years without much examination of its error rate, which prevents transparent about if and how often BPA experts make errors. In the past few years –especially since NAS [1] and others have raised concerns about BPA, as well as the courts' increasingly requiring error rates in Daubert hearings– research studies have started to examine error rates in BPA.

Two foundational studies in 2016 established error rates in BPA. The first study was with 27 BPA experts, all of which had at least 80 hours of training in BPA, and all had active casework experience of at least five years. Most importantly, they were all qualified by a court as an expert in BPA and have provided expert testimony in real casework. Results revealed an error rate of 13.1 % when analysts tried to identify bloodstain patterns on rigid surfaces [17] (see also [48]).

This error rate may well be an underestimation, due, for example, to ecological validity, as participants knew they were being examined, and/or the test items in the studies were easier than those in casework, and/or never calculating inconclusives as potential errors. In contrast, it may overestimate the error rates, if, for example, there is proper blind peer review, and/or the test items in the studies are more difficult than those in casework (as detailed in other sections of this article, see also [46]).

The second extensive study, where analysts examined stains on fabric surfaces, revealed a higher error rate. In this study, 37 BPA experts were tested, and again, all of the participants had at least 80 hours of training in BPA, all had active casework experience of at least five years, and all were court qualified as an expert in BPA and have provided expert testimony. This study found that 23.4 % of the BPA analysts' decisions were erroneous [13].

As explained earlier, and elaborated on in [46], the difficulty of the test items plays a critical role in the resulting error rate. Hence, this study found a higher (10%) error rate when test items were from fabric surfaces which are more difficult than items from rigid and non-absorbent surfaces [17]. Indeed, "fabric surfaces are complex and highly variable with factors such as fiber composition, structural characteristics, surface treatments, dyeing, wear, and laundering, all potentially affecting the final appearance of a bloodstain" (page 5, [13]).

If error rate studies do not reflect casework, then they produce misleading error rates [46]. Specifically in BPA, "despite the frequency of clothing examinations in forensic laboratories around the world, the dynamics of bloodstain formation on textile surfaces remains under-researched" (page 5 [13]). If BPA error rate studies do not include bloodstains on clothing, that is an issue because they do not reflect actual casework [46]. This is especially a problem since such studies produce artificially low error rates as they do not include surfaces that are more complex and thus produce a higher error rate.

Furthermore, it is important to note that these numbers may well understate the error rate because when calculating the 13.1% error rate (for stains on the easier rigid surfaces), they only counted conclusions where the BPA experts were confident in their conclusions. But 17.4% of the time, the BPA experts chose 'not to decide' and responded with an 'inconclusive' decision. Excluding the inconclusive decisions, BPA experts reached the correct decision 69.5 % of the time. The correctness of the 17.4% of inconclusive decisions is between 0% to 17.4% (sometimes inconclusive decisions are correct, sometimes they are errors [49]). If all of the inconclusive decisions were correct, then the BPA reached correct conclusions 86.9% of the time, whereas if all of them were errors, then the BPA reached correct conclusions 69.5% of the time, giving an error rate range of 13.1–30.5%. We cannot determine how many of the inconclusive decisions were in error, but we do know that inconclusive decisions occur most often in the more difficult test items, where errors are more likely to occur [46,47].

In addition, we must remember that even in the study using only rigid surfaces, it did not include test items that are common, but more difficult, such as surfaces that have coatings [14] or/and absorbent surfaces, which can distort the bloodstain pattern [50].

Thus, the test items used to produce an error rate (e.g., 13.1%) probably give an error rate that underestimates the error rate in actual casework. The difference between the error rates involving bloodstains on rigid surfaces and fabrics is only one demonstration of how error rate studies may underestimate the actual error rates in casework (not to mention how responses are scored, ecological validity, etc. –see above and [46,47,49]).

It is important to emphasize and to also note that these studies only examined classification error –not crime scene reconstruction errors. In the former, a BPA analyst examines, for example, a collection of spatter bloodstains on a wall, and potentially can conclude the directionality of the bloodstains and the position of the blood source. In the latter, the analyst extends their conclusions to activity level, e.g., that the spatter bloodstains show that the victim was stabbed in the neck. Reconstruction involves more than just classification and thus is likely to have higher errors than just classification decisions (not to mention that it is also more susceptible to bias due to greater exposure to contextual irrelevant information). Hence, the error rates found in the studies above only reflect the lower classification errors.

For example, a 2017 study that examined error rates for "swipe and wipe patterns", the transfer patterns commonly encountered at bloodied scenes found that "correct classifications of pattern types were problematic, with an overall error rate of 32%" [51]. The errors in reconstruction and activity level are not represented and reflected in such classification error studies (see also below), and reconstruction errors are going to have even higher error rates.

This is especially problematic, as reconstruction and activity level opinions are used by and relied upon in police investigations as well as by the courts. Reconstruction and activity conclusions require accurate bloodstain classification, but in addition are also based on further knowledge of activities and events, that not only add complications, but also often biasing contextual information.

Even in classification errors, the most recent and most-extensive "large scale rigorous evaluation of the accuracy… of practicing bloodstain pattern analysts' conclusions" (page 5 [15]), further replicate the concerning error rates found in the previous classification studies. In this study 75 practicing bloodstain pattern analysts examined 192 bloodstain patterns, and the data revealed that they "were often erroneous and often contradicted other analysts" (page 7 [15]). This is in classification errors, not the higher error rates for reconstruction and activity level. As the study's authors state "these results suggest that if two BPA analysts both analyze a pattern… they cannot always be expected to agree, and if they do agree they may both be wrong" (page 5 [15]).

6. Recommended Way Forward

The concerns raised in this article do not mean that BPA cannot be a legitimate scientific forensic domain. However, it does raise serious concerns about BPA and how some of BPA is practiced and presented in court. Moving forward and improving BPA first requires acknowledging the (potential) issues and weaknesses that may need to be addressed. Raising and considering such (potential) issues may not be comfortable and indeed it often draws defensive push-back responses, but such difficult discussions are necessary and are a prelude for moving forward and making improvements.

One major issue relates to BPA experts saying 'more than they should', 'more than is justified to conclude' based on the evidence. In other words, problems arise when the meaning of the evidence is overstated. By doing so, the entire BPA domain (including legitimate aspects) is put at risk. This is what happened in bitemark analysis: Examiners overstated the meaning of the evidence. Now bitemark evidence —-including cases where it can draw legitimate conclusions and make valuable contributions– are no longer allowed in many courts. For BPA not to end up in that situation, BPA examiners must limit themselves to what they can legitimately conclude and state.

Other issues raised in this article can also be dealt with. For example, the issue of bias can be minimized considerably by avoiding irrelevant contextual information and optimizing the sequencing of the task relevant information (see LSU-E [42], which can also increase reliability). If/when BPA examiners are exposed to task irrelevant contextual information (sometimes it is unavoidable because BPA analysts are usually present at the crime scene and therefore the issue of limiting irrelevant contextual information or implementing linear sequential unmasking is more challenging), then being transparent about it and detailing it in the forensic report and in testimony is warranted.

The BPA Report and court testimony should also point out alternative theories and explanations, and the scope and limits of the conclusions (BPA experts, like all other forensic experts, should be committed to the science, and be impartial regardless of whether they are working for the prosecution or the defence, and should not see themselves as 'crime fighters'). Of course, BPA needs agreed clearly defined classification methods [43].

As already detailed in this article, there are some very good and encouraging efforts to move forward and improve BPA (e.g., [40]). Hopefully this article will contribute to advancing BPA and avoiding dangerous pitfalls.

7. Summary and conclusions

Only recently has BPA started to be examined and researched more closely. These examinations have revealed serious questions and concerns about BPA:

Validity: Its theoretical underpinnings (e.g., the relationships between 'causes' and 'resulting bloodstain pattern' (one-to-one versus many-to-one)) have yet to be sufficiently researched or understood. Its practical underpinnings –the actual physics and mathematical calculations involved in BPA– have many complex interacting variables that make it almost impossible for analysts to calculate in most BPA cases. Hence, they resort to subjective non-scientific judgments.

Reliability: Studies have repeatedly shown that BPA experts provide conclusions that are not reliable, thus there is limited consistency (reproducibility, repeatability) of their conclusions. Often BPA experts will give different and conflicting conclusions about the same bloodstain.

Bias: BPA experts' judgments are influenced by contextual information and cognitive bias, which can distort analysis and result in erroneous conclusions. BPA is especially susceptible to such biases due to the high subjectivity currently involved in BPA practice, as well as their very high exposure to contextual information (often before they even see and examine the bloodstain pattern).

Error rate: All the studies on error rate in BPA have shown that BPA analysts have an alarming level of errors. There is good reason to conclude that even the high level of error rates found in the various aspects of BPA actually underestimate the true error rate in casework.

It is important to note that these issues refer to BPA as it is practiced and has been practiced. Many of these issues can (and should) be addressed so as to improve the practice of BPA, such as taking measures to reduce bias [40,42].

Declaration of competing interest

The author declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] National Academy of Sciences (NAS): Strengthening Forensic Science in the United States: A Path Forward. 2009. Washington, DC: National Academies Press (pp. 1-348). doi: 10.17226/12589. https://nap.nationalacademies.org/login.php?record_id=12589 (last downloaded on 1 November 2023).

[2] President's Council of Advisors on Science and Technology (PCAST). Forensic science in criminal courts: Ensuring scientific validity of feature-comparison methods. 2016 (pp. 1-174). https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/PCAST/pcast_forensic_science_report_final.pdf (last downloaded on 1 November 2023).

[3] National Commission on Forensic Science. Ensuring that forensic analysis is based upon task-relevant information. 2015 (pp. 1-9). https://www.justice.gov/ncfs/file/818196/download (last downloaded on 1 November 2023).

[4] Campbell A. The Fingerprint Inquiry Report. Scotland. 2011 (pp. 1-790). https://web.archive.org/web/20150221081642/http://www.thefingerprintinquiryscotland.org.uk/inquiry/files/TheFingerprintInquiryReport_Low_res.pdf (last downloaded on 1 November 2023).

[5] Office of the Inspector General (OIG). A review of the FBI's handling of the Brandon Mayfield case. 2006 (pp. 1-33). Office of the Inspector General, Oversight and Review Division, US Department of Justice. https://oig.justice.gov/sites/default/files/archive/special/s0601/final.pdf (last downloaded on 1 November 2023).

[6] Dror IE, Hampikian G. Subjectivity and bias in forensic DNA mixture interpretation. Sci Justice. 2011;51:204-8. doi: 10.1016/j.scijus.2011.08.004.

[7] G. Cooper, V. Meterko, Cognitive bias research in forensic science: a systematic review, Forensic Sci. Int. 297 (2019) 35–46, https://doi.org/10.1016/j.forsciint.2019.01.016.

[8] Kukucka J, Dror IE. Human factors in forensic science: psychological causes of bias and error. In D. DeMatteo and K. Scherr (Eds.), The Oxford Handbook of Psychology and Law. 2023 (pp. 621-C36P212) . Oxford University Press. doi: 10.1093/oxfordhb/9780197649138.013.36.

[9] B. Garrett, P. Neufeld, Invalid forensic science testimony and wrongful convictions, Virginia Law Rev. 95 (2009) 1–97.

[10] Dror IE. The most *consistent* finding in forensic science is *inconsistency*. J Forensic Sci 2023;68(6): 1851–1855. doi: 10.1111.1556-4029.15369.

[11] J. Butler, M. Kline, M. Coble, NIST interlaboratory studies involving DNA mixtures (MIX05 and MIX13): Variation observed and lessons learned, Forensic Sci Int: Genetics. 37 (2018) 81–94, https://doi.org/10.1016/j.fsigen.2018.07.024.

[12] B. Ulery, A. Hicklin, J. Buscaglia, M. Roberts, Repeatability and reproducibility of decisions by latent fingerprint examiners, PLoS One 7 (2012) e32800, https://doi.org/10.1371/journal.pone.0032800.

[13] M.C. Taylor, T. Laber, P. Kish, G. Owens, N.K.P. Osborne, The reliability of pattern classification in bloodstain pattern analysis – part 2: bloodstain patterns on fabric surfaces, J. Forensic Sci. 61 (2016) 1461–1466, https://doi.org/10.1111/1556-4029.13191.

[14] S. Shiri, K. Martin, J. Bird, Surface coatings including fingerprint residues can significantly alter the size and shape of bloodstains, Forensic Sci. Int. 295 (2019) 189–198, https://doi.org/10.1016/j.forsciint.2018.12.008.

[15] A. Hicklin, K. Winer, P. Kish, C. Parks, W. Chapman, K. Dunagan, N. Richetelli, et al., Accuracy and reproducibility of conclusions by forensic bloodstain pattern analysts, Forensic Sci. Int. 325 (2021) 110856, https://doi.org/10.1016/j.forsciint.2021.110856.

[16] James SH, Kish PE, Sutton TP. Principles of Bloodstain Pattern Analysis: Theory and Practice. 2005 (pp. 1-572). CRC Press. Boca Raton, FL.

[17] M.C. Taylor, T. Laber, P. Kish, G. Owens, N.K.P. Osborne, The reliability of pattern classification in bloodstain pattern analysis, part 1: bloodstain patterns on rigid non-absorbent surfaces, J. Forensic Sci. 61 (2016) 922–927, https://doi.org/10.1111/1556-4029.13091.

[18] G. Griffiths, E. Lisco, D. Northfield, Accuracy of area of origin analysis on textured, wallpaper surfaces, J Bloodstain Pattern Anal. 35 (2020) 9–19.

[19] P. De Forest, P. Pizzola, B. Kammrath, Blood Traces: Interpretation of Deposition and Distribution, John Wiley and Sons, 2021, pp. 1–384.

[20] Bevel T, Gardner RM. Bloodstain pattern analysis with an introduction to crime scene reconstruction. 2008 (pp. 1-44). CRC Press.

[21] D. Attinger, K. Brabanter, C. Champod, Using the likelihood ratio in bloodstain pattern analysis, J. Forensic Sci. 67 (2022) 33–43, https://doi.org/10.1111/1556-4029.14899.

[22] International Association of Bloodstain Pattern Analysis (IABPA). Bloodstain Pattern Analysis Basic Course Requirements. 2023 (pp. 1-6). https://iabpa.org/docs/RevEduc.pdf (last downloaded on 1 November 2023).

[23] R. Arthur, S. Cockerton, K. Bruin, M. Taylor, A novel, element-based approach for the objective classification of bloodstain patterns, Forensic Sci. Int. 257 (2015) 220–228, https://doi.org/10.1016/j.forsciint.2015.08.028.

[24] Y. Liu, D. Attinger, K. Brabanter, Automatic Classification of Bloodstain Patterns Caused by Gunshot and Blunt Impact at Various Distances, J. Forensic Sci. 65 (2020) 729–743, https://doi.org/10.1111/1556-4029.14262.

[25] T. Zou, H. Stern, Towards a likelihood ratio approach for bloodstain pattern analysis, Forensic Sci. Int. 341 (2022) 111512, https://doi.org/10.1016/j.forsciint.2022.111512.

[26] S. Siu, J. Pender, F. Springer, F. Tulleners, W. Ristenpart, Quantitative Differentiation of Bloodstain Patterns Resulting from Gunshot and Blunt Force Impacts, J. Forensic Sci. 62 (2017) 1166–1179, https://doi.org/10.1111/1556-4029.13418.

[27] Kahneman D, Sibony O, Sunstein CR. *Noise: a flaw in human judgment*. 2021. William Collins.

[28] Kosslyn SM, Koenig O. Wet mind: The new cognitive neuroscience. 1995 (pp. 1-548). New York, NY: The Free Press.

[29] Nickerson RS. Confirmation bias: a ubiquitous phenomenon in many guises. Rev Gen Psych. 1998;2:175–220. doi: 10.1037/1089-2680.2.2.175.

[30] I.E. Dror, Cognitive and Human Factors in Expert Decision Making: Six Fallacies and the Eight Sources of Bias, Anal. Chem. 92 (2020) 7998–8004. https://pubs.acs.org/doi/10.1021/acs.analchem.0c00704.

[31] Gilovich T, Griffin D, Kahneman D. Heuristics and biases: The psychology of intuitive judgement. 2002 (pp. 1-882). New York, NY: Cambridge University Press.

[32] S.M. Kassin, I.E. Dror, J. Kukucka, The forensic confirmation bias: Problems, perspectives, and proposed solutions, J Appl Res Memory Cognition. 2 (2013) 42–52, https://doi.org/10.1016/j.jarmac.2013.01.001.

[33] A. Tversky, D. Kahneman, Judgement under uncertainty: Heuristics and biases, Science 185 (1974) 1124–1131, https://doi.org/10.1126/science.185.4157.11.

[34] Z. Kunda, The case for motivated reasoning, Psych Bulletin. 108 (1990) 480–498, https://doi.org/10.1037/0033-2909.108.3.480.

[35] E. Balcetis, D. Dunning, See what you want to see: Motivational influences on visual perception, J Personality Social Psych. 91 (2006) 612–625, https://doi.org/10.1037/0022-3514.91.4.612.

[36] C. Eeden, C. Poot, P. Koppen, The forensic confirmation bias: a comparison between experts and novices, J. Forensic Sci. 64 (2019) 120–126, https://doi.org/10.1111/1556-4029.13817.

[37] Dror IE. Biases in forensic experts. Science. 2018;360(6386):243. https://www.science.org/doi/full/10.1126/science.aat8443.

[38] Forensic Science Regulator. Lessons Learnt: Contextual Bias in Forensic Toxicology. 2019. Forensic Science Regulator https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/919152/Lessons_Learnt_Issue_3.pdf (last downloaded on 1 November 2023).

[39] N.K.P. Osborne, M.C. Taylor, M. Healey, R. Zajac, Bloodstain pattern classification: Accuracy, effect of contextual information and the role of analyst characteristics, Sci. Justice 56 (2016) 123–128, https://doi.org/10.1016/j.scijus.2015.12.005.

[40] OSAC Proposed Standard for Methodology in Bloodstain Pattern Analysis (2022-S-0030). May 2023 (pp. 1-10). https://www.nist.gov/system/files/documents/2023/07/03/OSAC%202022-S-0030%20Standard%20Methodology%20in%20Bloodstain%20Pattern%20Analysis.pdf (last downloaded on 1 November 2023).

[41] Osborne NKP, Zajac R, Taylor MC. Bloodstain pattern analysis and contextual bias. 2015. Wiley Encyclopedia of Forensic Science. doi: 10.1002/9780470061589.fsa1127.

[42] I.E. Dror, J. Kukucka, Linear Sequential Unmasking–Expanded (LSU-E): A general approach for improving decision making as well as minimizing noise and bias, Forensic Sci. Int.: Synergy 3 (2021) 100161, https://doi.org/10.1016/j.fsisyn.2021.100161.

[43] E. Hook, S. Fieldhouse, D. Flatman-Fairs, G. Williams, Bloodstain classification methods: A critical review and a look to the future, Sci. Justice 4 (2024) 408–420.

[44] OSAC Proposed Standard OSAC 2023-S-0026 Technical Report for Task-Relevant Information in Friction Ridge Examination https://www.nist.gov/system/files/documents/2024/10/04/OSAC%202023-S-0026%2C%20Technical%20Report%20for%20Task-Relevant%20Information%20in%20Friction%20Ridge%20Examination%20Version%202.1.pdf.

[45] I.E. Dror, D.A. Wolf, G. Phillips, S. Gao, Y. Yang, S.A. Drake, Contextual information in medicolegal death investigation decision-making: Manner of death determination for cases of a single gunshot wound, Forensic Sci. Int.: Synergy 5 (2022) 100285, https://doi.org/10.1016/j.fsisyn.2022.100285.

[46] I.E. Dror, The Error in 'Error Rate': Why error rates are so needed, yet so elusive, J. Forensic Sci. 65 (2020) 1034–1039, https://doi.org/10.1111/1556-4029.14435.

[47] I.E. Dror, N. Scurich, (Mis)use of scientific measurements in forensic science, Forensic Sci. Int.: Synergy 2 (2020) 333–338, https://doi.org/10.1016/j.fsisyn.2020.08.006.

[48] Laber T, Kish P, Taylor M, Owens G, Osborne NKP, Curran J. Reliability Assessment of Current Methods in Bloodstain Pattern Analysis. 2014 (pp. 1-84). NIJ/NCJRS Report 247180. https://www.ojp.gov/pdffiles1/nij/grants/247180.pdf (last downloaded on 1 November 2023).

[49] I.E. Dror, G. Langenburg, "Cannot decide": the fine line between appropriate inconclusive determinations vs. unjustifiably deciding not to decide, J. Forensic Sci. 64 (1) (2019) 10–15, https://doi.org/10.1111/1556-4029.13854.

[50] T. Castro, M. Taylor, J. Kieser, D. Carr, W. Duncan, Systematic investigation of drip stains on apparel fabrics: the effects of prior-laundering, fibre content and fabric structure on final stain appearance, Forensic Sci. Int. 250 (2015) 98–109, https://doi.org/10.1016/j.forsciint.2015.03.004.

[51] S. Yuen, M. Taylor, G. Owens, D. Elliot, The reliability of swipe/wipe classification and directionality determination methods in bloodstain pattern analysis, J. Forensic Sci. 62 (2017) 1037–1042, https://doi.org/10.1111/1556-4029.13298.