Forensic Science International 323 (2021) 110779

Contents lists available at ScienceDirect

Forensic Science International

journal homepage: www.elsevier.com/locate/forsciint

A different perspective on the forensic science crisis

Céline Weyermann[a,*], Claude Roux[b]

[a] Ecole des Sciences Criminelles, Université de Lausanne, Switzerland
[b] Centre for Forensic Science, University of Technology Sydney, Australia

ARTICLE INFO

Article history:
Received 13 November 2020
Received in revised form 19 February 2021
Accepted 5 April 2021
Available online 10 April 2021

Keywords:
Trace
Clue
Context
Investigation
Intelligence
Risks
Reasoning

ABSTRACT

Recurrent mentions of a forensic science crisis are reported in the literature. Some 15 years ago, the discussion was focused on the backlog problem. Other issues have been regularly debated since then, including the risk of error, need for independence, importance and risk of contextualisation, increasing fragmentation into separate processes and specialisations. Proposed solutions to solve one problem often led to other issues in other parts of the process. This paper attempts to address the apparent crisis using a different perspective, through a comparison with established disciplines, namely material science, medicine and historical science. The comparison with material science shows that, despite the varied organisational and legal models and the interdisciplinary nature of the field, a common element to all forensic science endeavours exists: the trace. A greater focus on the trace might thus help the development of a holistic approach in forensic science. The comparison with medicine demonstrates that, through the overall process, the main risk shifts from the risk to overlook important hypotheses or traces at the beginning of the process (e.g. problems in the detection of traces/symptoms and formulation of hypotheses) to the risk of supporting the wrong hypothesis at the end of the process (e.g. erroneous test of the hypotheses/diagnostic). Further, in medicine, symptoms are rarely evaluated in isolation, while traces are often evaluated separately. By analogy, epidemiology illustrates forensic science's critical role in preventing crime through forensic intelligence, supporting a more extensive and more collaborative application of forensic science in security issues. The comparison with historical science also indicates that a single trace (i.e. the observed effect) is rarely sufficient to reason on its cause. Retrodiction (abduction) is proposed as an alternative reasoning approach to reconstruct events from the past based on signs uncovered in the present. Finally, the impact of science in investigating crimes is presented as an evolving process. A new trace or information can bring an entirely different light on the reconstruction of past events or prevention of future issues. Thus, issues or challenges in the first stages of the process (i.e., crime scene investigation) should be addressed in priority for subsequent stages to function correctly.

1. Introduction

From the beginning, forensic science has lacked consensus about what it is and what it does. For example, Kirk defined it as a law-science profession and preferred the term criminalistics [1], while Locard argued that it was not a science but a (police) technique or scientific method supporting the criminal investigation [2].[1] Later, Kind considered a broader view of forensic science using the term of investigation science closer to the notion of scientific policeman previously proposed by Vollmer [3–5].[2] Such distinctions or confusion still exist today, including in the literature where forensic science is sometimes referred to as applied science, a profession, a set of techniques, a broad range of disciplines or a scientific problem-solving endeavour [6–9]. Thus, forensic science largely remains undefined, and it appears that not only stakeholders but also many forensic practitioners may not be talking about the same things. Further, many individuals not educated in or not working as forensic scientists (e.g. lawyers, statisticians or psychologists) regularly give their opinion on what forensic science should or should not be, thus further complicating the perpetual debate on forensic science.

Since the release of the NAS report [9], continuous statements and warnings about a crisis in forensic science have been raised

* Corresponding author.
E-mail address: celine.weyermann@unil.ch (C. Weyermann).

[1] It is interesting to note that, while portraying forensic science supporting investigation, Locard had to locate his newly created police laboratory in the attic of the Lyon courthouse in 1910 leading to some independence from the Police Department.

[2] Like Kind, Vollmer was a police manager, realising the potential of science in the investigation early on. Vollmer initiated and participated to academic education in police administration, criminology and criminalistics.

https://doi.org/10.1016/j.forsciint.2021.110779
0379-0738/

among and outside the forensic science community, highlighting the need for (urgent) improvements [1,6,10–23]. Proposed recommendations include constant requirements for more resources (in practice, research and education) and the need for increased quality management based on the observation of past errors and shortcomings [9,24]. The need for more adaptability to face present and future challenges has also been recently raised [10,22].

The NAS report, and later the PCAST report, primarily focused on issues such as backlogs (e.g. DNA analysis) and risk of errors (e.g. pattern comparison) in the USA [9,25]. Even though improvements are always possible and welcome, it could be argued that the original crisis emphasised in these reports has mostly been addressed and at least partly been resolved [24,26–30].[3] However, it also appears that many real or perceived problems within the community are persistent [15,17,18,25,31–34]. It seems we have reached the stage where there is a significant discussion, but any proposed way forward invariably leads us to the same intractable crossroads [35]. As an illustration, solutions offered by some forensic scientists and organisations (e.g. need for organisational independence and isolation from context to avoid bias [29,36–38]) are to some extent incompatible with other suggestions for improvements (e.g. need to defragment forensic science and increase involvement in the first stage of the investigation including the crime scene [10,15,19,39]). It begs the question: are the different stakeholders talking about the same crisis? In other words, are we not faced with several overlapping crises confusing the understanding of the root causes of the problems? And are we not overlooking the critical challenge of establishing and developing forensic science as a discipline?

This paper will take a few steps back to investigate these questions and review the forensic science 'crisis' through different prisms, namely other established disciplines: material science, medicine, and historical science. This approach will assist us in outlining a tentative transversal understanding of forensic science as a discipline. Our observations and reflections will guide possible relevant future developments to help the discipline forward.

2. What is forensic science?

Few publications address this question, but it is clear that different models and applications of forensic science co-exist, and are sometimes opposed, in the literature [6,10,39,40]. Thus, before the forensic crisis can be investigated, it is necessary to uncover various co-existing views and models. The latter are highly dependent on the jurisdiction or region of the world due to differences in the legal system, police organisation and academic setting. Depending on the judicial organisation, forensic scientists participate in crime scene investigation or work in laboratories [15]. In some countries, forensic scientists can also work as intelligence analysts[4] [10,41]. Some forensic scientists are specialists of one type of trace (e.g. this is often the case for body fluids and DNA analysis). In contrast, others work across a wide range of traces (e.g. fibre, glass, paint, soil and gunshot residue, often referred to as chemical criminalistics) [16,42].

Some forensic scientists are police officers, while others are civilians (working for police organisations, public or privatised laboratories, sometimes even as independent experts). Some are fully educated as forensic scientists, while others have varied, sometimes mixed, scientific backgrounds.

Further, technology and processes are often discussed as being essential to forensic science. However, they remain tools that evolve with time and should not be confused with the discipline itself (the end justifies the mean, not the opposite [1,6]). Finally, while scene investigation is central to forensic science, it cannot entirely define it as a discipline (and remains rarely attended by scientists [15]). In summary, there seems to be no unified view of what forensic science is and what it does.

From the discussion above, it appears that many dimensions relevant to forensic science fail to define the discipline accurately (e.g. legal systems, roles, educational backgrounds, methods). We suggest considering a different perspective to progress the discussion: forensic science models may be close to those from other more recent interdisciplinary sciences, such as material science, where practice, research and education are also very diverse. The only common point to all material science models is *the material*, as the object of study (presenting an infinite number of possible matters such as metals, ceramics, polymers and composites). In forensic science, a central common point to the variety of models is *the trace* [43] (that may be present in an infinite number of shapes and forms such as human, material or digital traces). Thus, in parallel to material science,[5] forensic science could be defined as *the scientific study of the properties and application of traces.* This definition is only embryonic at this stage and needs to be discussed and elaborated further within the forensic community. However, it represents an essential first step towards a more coherent discipline, assisting us in moving forward together.

3. From the observation of symptoms to a diagnostic

While the parallel with material science makes sense given the variety of co-existing models in both disciplines, forensic science has also been compared to medicine for several relevant reasons, not the least because medical doctors were among the pioneers in forensic science[6] and still represent a large part of the forensic community [5,6,11,12,35,44–46]. Similarities between medicine and forensic science have been noticed about the diagnostic approach based on the study of symptoms as signs of potential health issues (e.g. fever, cough) and the crime scene investigation based on the detection and study of traces as signs of criminal activities (e.g. blood, gunshot residue) [12,45]. The parallel has also been drawn between epidemiology and intelligence [12]. Both endeavours are based on multi-cases analysis and monitoring to understand disease/crime patterns better and support the definition of prevention actions (e.g. social distancing or hotspots avoidance) [41,47–49].[7] Moreover, several issues and challenges identified in the literature are also shared between these disciplines. Typical examples include backlogs and triage issues, risks of error, unstructured knowledge acquisition by practitioners, operating in different legal systems and functions, the need for flexibility to quickly detect and address emerging issues, the importance of generalists and specialists.

3.1. Criminal and medical investigations

An investigation/examination aims to search for relevant (sometimes latent) traces or symptoms in both disciplines. Hypotheses about the activities/diseases at the source of the observed clues are formulated and tested during the early stages of the investigation, thus often leading to a focused quest for further information/traces/

[3] https://www.nist.gov/topics/organization-scientific-area-committees-forensic-science (last access: June 2020)

[4] Forensic intelligence analysts examine forensic case data collected from several cases and extract information from repetitive patterns, considering series of cases committed from the same (group of) author(s) or studying general criminal trends.

[5] Material science can be defined as *the scientific study of the properties and applications of materials* (https://www.sciencedaily.com/terms/materials_science.htm and https://www.merriam-webster.com/dictionary/materials%20science, last access: June 2020).

[6] For example, Edmond Locard studied law and medicine.

[7] https://www.who.int/emergencies/diseases/novel-coronavirus-2019 and https://www1.health.gov.au/internet/main/publishing.nsf/Content/novel_coronavirus_2019_ncov_weekly_epidemiology_reports_australia_2020.htm (last access: June 2020).

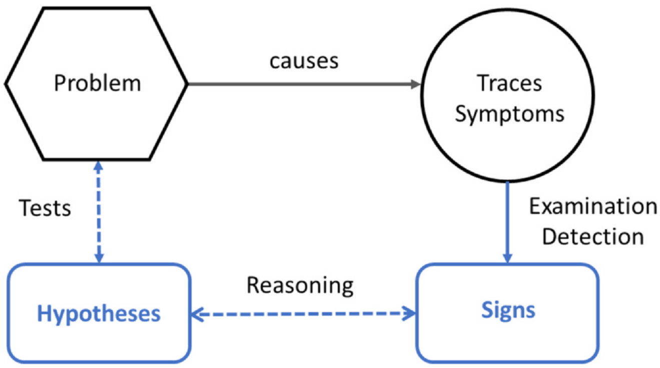

Fig. 1. A problem (e.g. crime, disease) causes the transfer of traces or the apparition of symptoms. The black lines indicate facts (real world) the investigation aims to reconstruct through reasoning (cognition indicated by blue lines). The investigation endeavours to detect relevant traces/symptoms (i.e., signs of what happened). Hypotheses are formulated (abduction) and tested (deduction) through a cyclic iterative process. This figure is inspired by the hypothetic-deductive cycle proposed by Ribaux et al. [51]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

symptoms in a cyclic hypothetic-deductive reasoning process [16,20,39,50] (see Fig. 1). The reasoning may address different types of questions relevant in a specific context (see examples in Table 1).

However, a diagnostic is generally more dynamic than a forensic reconstruction, as the state of the human body cannot be protected from outside influence like a (crime) scene. It has disadvantages but also advantages as more information can be collected as the situation evolves.

It is essential to remember that several causes may explain the observations (i.e. traces or symptoms). Indeed, DNA on a knife handle may have been transferred by a legitimate activity (e.g. cutting bread) or an unlawful activity (e.g. stabbing another person). Similarly, a high fever may be caused by seasonal flu or COVID-19. One symptom or trace will generally not be enough to infer the activity/disease with a sufficient degree of certainty. Thus, it is crucial to collect a wide range of traces and symptoms and formulate and test many possible explanations in an investigation's early stage.

Unfortunately, the same disease may generate different symptoms for different people (or even a lack of easily detectable symptoms), just like the same type of criminal activities may leave various traces due to many intrinsic and extrinsic factors influencing the generation or transfer and persistence of traces. Thus, both forensic science and medicine have to work on incomplete and highly variable data. And in both disciplines, severe cases (e.g. suspicion of murder/cancer) will be treated very differently than benign conditions or volume crime (e.g. theft/common cold). Both also (occasionally) suffer from system overloading leading to long delays for some type of consultation/treatment or case/trace respectively. Triage solutions have been implemented based on the seriousness of the cases and the feasibility of treatment/analysis [52].

The parallel can also be extended to the need of both generalists and specialists working in collaboration in an interdisciplinary approach to resolving complex health/crime issues. Indeed, to reach a diagnostic, a doctor generally relies on many different sources of information, including patient interview and context, such as previous episodes in the health history of the patient. When circumstances change, or new symptoms/traces are detected, then the diagnostic is revised until a sufficient level of confidence is reached to move to the treatment/judgement phase [5,16,53]. It is interesting to note that patients are not always satisfied with the diagnosis (or lack thereof) leading to the consultation of several doctors and receiving sometimes different or competing diagnoses and suggestion of treatments (based on a difference in the detection and evaluation of relevant symptoms for the examination of the same patient). Similarly, second expert opinion is frequent in forensic science (particularly in the adversarial systems) and sometimes lead to very different results and interpretations. The uncertain and evolutive nature of the diagnostic phase is illustrated in Case Study 1. This phenomenon referred to as "entropy" has recently been discussed in forensic science, the reasoning shifting continuously from hypotheses development (abduction) to hypotheses testing (deduction) [39,54]. Bayes theorem has been suggested as a deductive mathematical model to evaluate the results under alternative hypotheses [55,56].

Case Study 1. The uncertain and evolutive nature of diagnostic.

A patient known from the authors suffered from a relatively severe and recurrent allergic reaction. Main symptoms were a skin reaction and abdominal pains. Within two weeks, the patient consulted three doctors, and each of them reached a different diagnosis based on the same symptoms. The diagnosis was also based on questions about activities such as food ingestion, contact with various substances and exposure to stress. Different treatments were tried until the source was found: a laundry detergent that was only occasionally used. The fact that the patient was travelling (thus not continually sleeping in the same "contaminated" bedsheets) and that abdominal pains were also observed certainly added confusion to reach a diagnostic with any degree of certainty (as food allergy was among the prime suspects). One doctor was convinced that the abdominal pains were coming from another source and ordered a scan in a different hospital. However, the hospital specialists refused to perform the scan as they thought it would not bring relevant information. What would we say if three forensic scientists, observing the same traces, formulated different hypotheses? Further, what if one of them worked for the defence and the other for the prosecution, thus antagonising their reflections instead of pooling them in a collaborative thinking approach of scientific testing of the different hypotheses? Working in silos, of course, makes it more challenging to understand and resolve complex real-life problems. Depending on the (still unknown) source a gastroenterologist and a dermatologist may not be able to efficiently solve the problem alone, highlighting the generalist practitioner's importance to coordinate efforts and pool all the available information from the early stage of the investigation.

Many changes in forensic science have been driven by the requirement to minimise and correct errors. In the literature, many authors speak of type I and II errors. Type I errors generally refer to false-positive results (e.g. a person is falsely identified as being at the

Table 1
Example of questions that can be asked in forensic science and medicine.

Type of information	Forensic science	Medicine
Detection	Did a crime happen?	Is a person suffering from a health problem?
	What are the relevant trace(s) that can be detected?	What are the relevant symptom(s) that can be detected?
Localisation	Where is the trace(s) at the scene?	Where is the symptom(s) on/in the human body?
Chronology	When were the traces generated and in which sequence?	When did the symptoms first appear, and how did they evolve?
Identification	Who/what is the source of a trace?	What is the source of a symptom?
Reconstruction	What activities may have caused the generation of the traces?	What activities/lifestyle may be contributing to the observed symptom(s)?

In forensic science, questions about the source (who, what) are generally differentiated from questions about activities (where, when, how) [8]. Such differentiation may be less crucial in medicine.

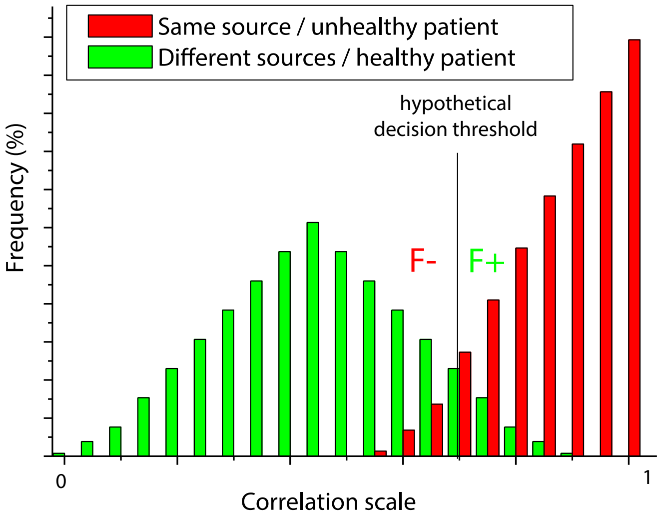

Fig. 2. Correlations between the features of specimens of known origin are often used in medicine and forensic science to support the decision-making process. Medicine aims at differentiating "unhealthy" from "healthy" patients, while in forensic science the aim is to differentiate specimen originating from the "same source" from specimen originating from "different sources". While the ideal method would return no overlapping populations, in reality, overlapping is very frequent and leads to a risk of false-positive (F+) or negative (F-) decisions. Even a probabilistic approach cannot erase this risk. It only aims at characterising/communicating the risk more explicitly than a decision threshold. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

source of a trace or action vs a person is incorrectly diagnosed for a disease) and type II errors generally refer to false-negative results (e.g. a person is falsely excluded as being at the source of the trace vs a person is incorrectly diagnosed as healthy).

Ideally, a methodology tends to minimise all error types; however, this is not always possible due to the variable nature of the traces/symptoms (i.e. high variability can be observed between the traces/symptoms from the same source/disease – see the spread of green bars in Fig. 2) and the discriminating power of the selected features (i.e. overlapping features may be observed between traces/symptoms from different sources/health status – see red bars overlapping the green bars in Fig. 2). Thus, when a decision must be made, the decision-makers have to consider the risks of error. It was suggested that error type II should be minimised early in the investigation (i.e., the risk to overlook some alternatives). In contrast, error type I should be minimised in the later stages (i.e., the risk of supporting the wrong hypothesis) [39]. Thus, while an appropriate balance has to be reached in the decision-making process of all criminal and medical inquiries, it is essential to understand that the balance is shifting from the risk not to consider enough hypotheses at the beginning of an investigation to the risk to support the wrong hypothesis during trial.

In forensic science manifold solutions have been proposed to minimise or characterise risks such as increasing quality management, decreasing bias or applying statistical models [9,17,24,29,36,55,56]. A detailed comparison is out of the scope of this article. However, new problems have been raised with each proposed solution [17,34,57]. Drawing the parallel to medicine, it is difficult to imagine a doctor inferring about the meaning of a single symptom in isolation to other observations to avoid bias or stopping to consider some symptoms because they can only be measured subjectively (e.g. pain or cough [58,59]). Unfortunately, no solution will allow us to avoid errors altogether. And as too much focus on reducing some type of errors may yield to an increase in other types of errors, even sometimes unsuspected errors in other parts of the process, an appropriate balance needs to be struck between the different risks [17,32].

A well-publicised case illustrating both the 'practical' risk of DNA contamination and the more complex risk of evaluating traces in isolation of other information is presented in Case Study 2.

Case Study 2. DNA contamination risks.

In the Farah Jama case (Australia, 2005), the verdict was based almost exclusively on DNA evidence. No other information confirmed that Mr Jama was linked to the alleged sexual assault [60]. *The conclusion of the forensic DNA analysis was correct: it was indeed Farah Jama's DNA. However, as later revealed, the DNA was not transferred through sexual intercourse with the victim. The DNA came from contamination of the collected specimen through a coincidental sequence of events, explaining that the suspect's DNA profile was in the database while he had committed no previously confirmed crime (see full report for more details* [60]*). While several recommendations have been issued to minimise the risk of contamination along the chain of "evidence", it will never be entirely possible to exclude this risk in practice given the increasingly lower sensitivity of the current techniques and the fact that contamination can occur even before the start of an investigation. In the Farah Jama case, the contamination occurred before the specimen arrived at the forensic laboratory. The failure of the forensic scientists and other actors (prosecutor, investigators, jurors) was then not of a technical nature, but due to interpretative deficiencies in the first stages of the investigation. A better understanding of the transfer and persistence of traces combined with the apparent lack of other information corroborating the suspect's involvement in the investigated event should have helped considering the risk of contamination as a potential alternative explanation for the presence of the suspect's DNA. Such an error might have been detected earlier if the information derived from the DNA trace had been better integrated with other relevant pieces of information during the investigation. The real challenge is for investigators and prosecutors to integrate forensic case data in an inter-disciplinary approach of hypotheses formulation and testing (as a clue among others rather than as an infallible scientific "gold-standard" evidence). This case illustrates well the cognitive bias called anchoring effects occurring when too much focus is given on a single initial piece of information (i.e., trace or hypothesis)* [61].

Risks may also be considered differently in medicine and forensic science due to the different role attributions in criminal vs medical investigations. Doctors are leading the investigation of their patient health. This is not the case in forensic science, where forensic scientists are rarely at the centre of the investigation of crime, although their central role in crime scene investigation regained interest recently [10,12,15]. Depending on the legal system, prosecutors or police detectives are generally leading and coordinating investigations, collecting clues from different sources such as crime scene investigation, witness interrogation, laboratory analysis or medico-legal examination. This leads to further differences between medicine and forensic science in the final decision-making stage. Prosecutors, judges and jurors base their decision to accuse and subsequently convict a person of interest on many elements, including forensic evidence, with generally no prior primary education in (forensic) science. Let's reflect on forensic scientists' position in the legal system and transpose it to the health care system. A cancer diagnosis and the most appropriate treatment decision would be left in the hands of 'jurors' having no prior education in medicine. This proposition would quickly be identified as absurd. Part of the erroneous interpretation of the information conveyed by traces may be due to misunderstandings on science's nature, as a knowledge building process rather than a universally acknowledged truth [18]. Like a witness statement, a trace is not without its limitation and should thus be considered together with all the collected information. However, in practice, barriers exists to the systematic exchange of information due to organisational, administrative and collaboration issues [39].

3.2. Intelligence and epidemiology

It is crucial to treat health problems on a case-by-case basis. However, it is also essential to limit the spread of diseases or health conditions through prevention measures (e.g. balanced diet, the practice of physical activity and relaxation or right working positions). Epidemiology can be described as studying diseases in a more general approach considering spread, control and incidence of diseases and other health issues [49]. For example, sports medicine will advise to warm-up and avoid uncontrolled speed before skiing. Such advice is based on a retrodictive analysis of sports accidents data to limit their occurrence.

Similarly, society needs to be able to deal with crimes when they occur, and whenever possible, to prevent them from happening. Reducing crime activity through different prevention measures is generally an important aim in our society. Prevention actions usually require proactivity and predictivity based on a retrodictive analysis of repetitive patterns [41]. Traces have a vital role to play in these intelligence-led processes [39,47]. Forensic intelligence has been proposed to improve search strategy on crime scenes, link crimes committed by the same author or group of authors, identify recurring issues and support policing to address and prevent crime and security issues [62–64]. For example, many burglaries committed in Winter in Switzerland occurred between 5 pm and 10 pm [39,64]. The modus operandi (reconstructed from traces and witness information) indicated that authors checked if anyone was present by looking for visible light through windows (particularly in houses and first-floor apartments). Prevention actions targeted the residents by advising them to switch the lights automatically when absent in the evening and police patrols were increased in risky neighbourhoods.

Considering the processes described above, it is interesting to add a third level of action that medical doctors and forensic scientists can help address (from the particular to general):

1) Case-by-case treatment (i.e. diagnosis and healing/investigation and judgement)
2) Prevention and reduction of cases (i.e. epidemiology/intelligence)
3) Balancing the impact of cases with the prevention measures on society (e.g. safety/security vs life quality/liberty)

While the first level is carried out in a regulated medical/judicial context, the two other levels are much more interdisciplinary. They can be carried out in many different settings (including political, economic, ethical). While punctual errors can have severe consequences in level 1 (as discussed above), only recurrent errors are problematic when addressing level 2 and 3. Indeed, a few errors have little impact when considering thousands of cases. In our daily routine, we tend to focus on level 1, treating harms on a case basis. Addressing higher levels represent a higher degree of complexity, in which decisions cannot be taken with only one aim and discipline in view. Particularly at level 3, the objectives of different disciplines (e.g. stopping an epidemic or reducing crime) have to be balanced against other societal, political, economic, legal, ethical or philosophical considerations (e.g. health and security risks have to be balanced with life quality and liberty). The COVID-19 crisis illustrates the importance of the three levels that must be addressed by medical doctors and other stakeholders in our society (see Case Study 3).

Case Study 3. The COVID-19 crisis.

Case-by-case treatment was addressed in priority even before the beginning of the pandemic. The second level was essential for early detection and warning of the problem, and when the systems became overloaded to 'flatten the curve' and reduce contagion. The third level was more complex to address, but as social distancing did not completely contain the disease long term impact of a shutdown on our society had to be balanced with preserving the health of all individuals. While many countries adopted similar measures, differences were also observed depending on the different contexts (e.g. the number of cases, the health systems' capacity, politico-social, economic and geographic settings). This stage necessitates that interdisciplinary groups of experts gather intelligence on the whole (continuously evolving) crisis to support (inherently political) decision-making. All three stages require a strong capacity for constant adaptability and critical thinking to address the continuously shifting risks. No standard solution can be defined for all locations and times.

4. Experimental or historical science?

While forensic science is often referred to as an applied or experimental science, it probably has more in common with a historical science [18,35]. While experimental scientists study regularities among types of events (e.g. laws of physics) and focuses on testing prediction (e.g. $E = mc^2$ [65]), historical scientists investigate particular past events (e.g. dinosaur's extinction) and consider multiple (common cause) hypotheses for a given body of clues [66]. Hypotheses testing about past events is based upon the best explanation's inference rather than predictive success (or failure). Cleland states that the approach in historical science is not inferior to that of experimental science; it merely engages in a very different pattern *of evidential reasoning* [67]. This different approach is necessary for the reconstruction process due to time asymmetry (see Fig. 3). The use of traces to reconstruct past events highlights many similarities between forensic science and historical science such as retrodiction (similar to abduction [50]), the formulation and confrontation of alternative hypotheses, common cause explanation, recognition and analysis issues (see Case Study 4) [54,66–68]. For example, Cleland reports that [66]:

- observational data "*is collected in the messy, uncontrollable world of nature through field studies*" (rather than in controlled laboratory conditions) - showing the parallel to the crime scene environment;
- it is important to "*distinguish information that is currently inaccessible to scientists from information that is completely lost* " - illustrating the difference between the lack of available powerful tools (e.g. contact DNA analysis in the nineties) from persistence issues (e.g. the potential loss of DNA after the washing of clothes);

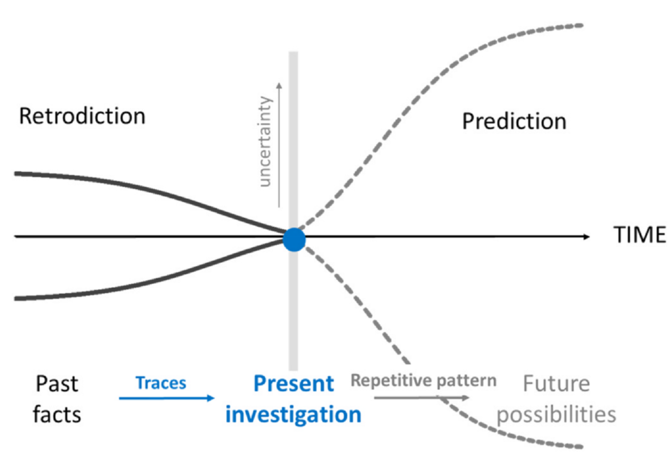

Fig. 3. Asymmetry of time: The past is over-determined while the future is under-determined. Retrodiction is based on traces from past events, while prediction is based on repetitive pattern detection. Both processes consider multiple hypotheses of what has happened or could happen. However, retrodiction uncertainty is lower as it investigates events that *did occur* through the interpretation of *existing traces* enabling a reasonable explanation of a common cause (figure inspired by [66]).

- "*the challenge (…) is recognising a trace for what it represents*"- illustrating the need to differentiate traces relevant to the investigated event from irrelevant traces (i.e., contamination or background noise [60]);
- "*considered in isolation, independently of the other lines of evidence, few traces would unambiguously count as a smoking gun for a hypothesis*" - demonstrating the importance of pooling observations and information together to formulate and test hypotheses;
- "*the principle of the common cause, which asserts that seemingly improbable associations among present-day traces of the past are best explained in terms of a common cause*" - illustrating the hypothetico-deductive reasoning allowing to reduce the number of hypotheses that can explain the observed traces;
- scientific hypotheses "*are tentative and subject to revision in light of new empirical discoveries or theoretical advances*" - showing the uncertain and iterative nature of an investigation.

This comparison confirms that while both historical science and forensic science require performant tools for their investigation, these disciplines' methodological approach is based on reconstructive reasoning that is, at least in part, different from experimental science. In addition to the essentially uncontrolled nature of the trace and the scene, these inferential differences have to be acknowledged by forensic scientists and stakeholders [18,43,69].

Case study 4. The smoking gun as a trace of past events.

As reported by Cleland, many different hypotheses were formulated to explain the extinction of the dinosaurs [54]: *climate change, extensive volcanism, pandemic, evolutionary senescence, nearby supernova and meteorite impact were considered plausible explanations given the lack of information available to palaeontologists. In 1980, Alvarez and Alvarez reported having found a high concentration of iridium in the K-Pg boundary separating the end of the Cretaceous from the beginning of the Paleogene (previously known as the Tertiary)* [66,70]. *This information referred to as a 'smoking gun' by Cleland* [54] *was a trace left by a past event at "precisely the time of the Cretaceous-Tertiary extinctions"* [70]. *Their discovery can be compared to the detection of a trace or sign indicative of what happened. The information extracted from that trace represented a clue supporting the hypotheses of an asteroid impact or a volcanic eruption. None of the other hypotheses explained the excess iridium.*

Further investigations led to the detection of additional 'traces' supporting meteorite impact over volcanism (e.g. presence of quartz showing a distinctive pattern indicative of a fracture) [66]. *While scientists focused on the 'best explanation' for the iridium anomaly, it is interesting to note that no elements allowed to 'falsify' the contagion hypothesis. Indeed, a pandemic could be responsible for the dinosaurs' extinction shortly before or after the impact. Cleland states that "a scientific consensus on the meteorite impact hypothesis for the K-Pg extinctions was reached because it explains an otherwise puzzling body of traces (e.g. iridium anomaly, shocked quartz, …)".*

5. Conclusion

In this paper, we first uncovered that forensic science may not be faced by one crisis, but several overlapping issues and challenges highly dependent on the contexts in which forensic science is applied. Thus, proposed solutions are rarely useful and implementable in all forensic contexts and may even lead to additional unsuspected problems at other parts of the process. We then examined these challenges using different perspectives, through the comparison with established disciplines, namely material science, medicine and historical science.

The comparison with material science illustrated that a discipline with an apparent lack of definition and with poorly defined and very variable principles can still have a central element. As a link between all forensic science endeavours, the trace may represent the basis to develop a solid core of unifying concepts and principles in forensic practice, research and education.

The comparison with medicine emphasized the need for a more holistic consideration of the traces available and contextual information in developing and testing hypotheses. This highlighted that the risks shift along the forensic science process, from overlooking possible explanations at the beginning of the process to supporting the wrong hypothesis at the end of the process (i.e. trial of diagnostic). Focusing too early on a set of alternative hypotheses may lead to subsequent problems if the wrong set of hypotheses are selected excluding other possible common cause explanations in the final evaluation. This supports the need to break the barriers between forensic scientists and other stakeholders as they work in a continuous process [39] where errors in the early stages (e.g. overlooking a potential explanation) may lead to severe mistakes at the end of the process (e.g. wrongful conviction – see Case Study 2). Comparison with medicine also shows the importance of forensic science in intelligence processes not only to improve criminal inquiries but also to prevent crimes and improve security.

Finally, the comparison with historical science showed essential differences between experimental science (often wrongly considered as a "better" scientific approach) and "historical" science (required to reason about past events as the causes of present-day traces). This comparison highlighted the importance of retrodiction (also called abduction) to formulate hypotheses about the source of traces, as signs of past events that need to be reconstructed. It also helps understand that scientific hypotheses are tentative and subject to revision in light of new information [66], as confirmed by the evaluative framework proposed to interpret forensic findings [55].

The comparisons undertaken in this paper may provide the key to address current and future challenges: a balance between (1) a solid core of unifying forensic science concepts and principles focused on the trace(s), (2) appropriate (iterative abductive and deductive) reasoning, and (3) flexibility to adapt to the large variety of purposes in different politico-legal systems using a variety of evolving experimental tools. It is also important to consider the impact of science in the investigation and prevention of crimes as a continuously evolving process. Thus issues in the first stages of the process (i.e., crime scene investigation) should be addressed in priority for subsequent stages to function correctly [15,39].

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CRediT authorship contribution statement

Céline Weyermann: Conceptualisation and writing. **Claude Roux:** conceptualisation and writing.

Declarations of interest

None.

Acknowledgements

We wish to dearly thank our colleague and mentor Prof. Pierre Margot, who greatly inspired this contribution through his definition of the trace, as well as his comparison of forensic science to medicine. We also wish to thank Robin Amacher for useful discussions on material science, and numerous forensic science colleagues for stimulating our reflections through multiple past and future discussions.

References

[1] P.L. Kirk, The ontogeny of criminalistics, J. Crim. Law Criminol. Police Sci. 54 (1963) 235–238.
[2] E. Locard, L'enquête Criminelle et les Méthodes Scientifiques, Flammarion, Paris, 1920.
[3] A. Vollmer, The scientific policeman, Am. J. Police Sci. 1 (1) (1930) 8–12.
[4] A. Vollmer, A. Schneider, School for police as planned at Berkeley, J. Am. Inst. Crim. Law Criminol. 7 (6) (1916) 877–898.
[5] S. Kind, The Scientific Investigation of Crime, Forensic Science Services, Harrogate, England, 1987, pp. 106–389.
[6] P.R. De Forest, Recapturing the essence of criminalistics, Sci. Justice 39 (3) (1999) 196–208.
[7] K. Inman, N. Rudin, Principles and practice of criminalistics - the profession of forensic science, Protocols in Forensic Science Series, CRC Press, 2001.
[8] K. Inman, N. Rudin, The origin of evidence, Forensic Sci. Int. 126 (1) (2002) 11–16.
[9] National Research Council, Strenghtening Forensic Science in the United States: A Path Forward, The National Academies Press, Washington, DC, 2009, https://doi.org/10.17226/12589
[10] E. Casey, O. Ribaux, C. Roux, The kodak syndrome: risks and opportunities created by decentralization of forensic capabilities, J. Forensic Sci. 64 (1) (2019) 127–136.
[11] P. Margot, Commentary on the need for a research culture in the forensic sciences, UCLA Law Rev. 58 (3) (2011) 795–801.
[12] P. Margot, Forensic science on trial - what is the law of the land, Aust. J. Forensic Sci. 43 (2011) 83–97.
[13] J.L. Mnookin, et al., The need for a research culture in the forensic sciences, UCLA Law Rev. 58 (3) (2011) 725–777.
[14] R.M. Morgan, E.A. Levin, A crisis for the future of forensic science: lessons from the UK of the importance of epistemology for funding research and development, Forensic Sci. Int. Synerg. 1 (2019) 243–252.
[15] D.S. Pietro, B.W. Kammrath, P.R. De Forest, Is forensic science in danger of extinction? Sci. Justice 59 (2) (2019) 199–202.
[16] C. Roux, O. Ribaux, F. Crispino, From forensics to forensic science, Curr. Issues Crim. Justice 21 (1) (2012) 7–24.
[17] S. Willis, Accreditation - straight belt or life jacket? Presentation to forensic science society conference november 2013, Sci. Justice 54 (6) (2014) 505–507.
[18] F. Crispino, et al., Is the (traditional) Galilean science paradigm well suited to forensic science? WIREs Forensic Sci. 1 (6) (2019) e1349.
[19] J. Robertson, Forensic science, an enabler or dis-enabler for criminal investigation? Aust. J. Forensic Sci. 44 (1) (2012) 83–91.
[20] O. Ribaux, B. Talbot Wright, Expanding forensic science through forensic intelligence, Sci. Justice 54 (6) (2014) 494–501.
[21] D.M. Risinger, M.J. Saks, A house with no foundation, Issues Sci. Technol. 20 (1) (2003).
[22] C. Roux, B. Talbot-Wright, J. Robertson, F. Crispino, O. Ribaux, The end of the (forensic science) world as we know it? The example of trace evidence, Philos. Trans. R. Soc. B: Biol. Sci. 370 (1674) (2015) 20140260.
[23] O. Ribaux, et al., Digital Transformations in Forensic Science and Their Impact on Policing, Policing in an Age of Reform - An Agenda for Research and Practice, Palgrave's Critical Policing Studies, Palgrave McMillan, 2021.
[24] A. Ross, W. Neuteboom, Implementation of quality management from a historical perspective:the forensic science odyssey, Aust. J. Forensic Sci. (2020) 1–13.
[25] President's Council of Advisors on Science and Technology (2016) Forensic Science in Criminal Courts: Ensuring Scientific Validity of Feature-Comparison Methods. Washington, DC: 〈https://obamawhitehouse.archives.gov/administration/eop/ostp/pcast/docsreports〉.
[26] S.M. Ballou, The NAS report: ten years of response, J. Forensic Sci. 64 (1) (2019) 6–9.
[27] G. Ribeiro, J.M. Tangen, B.M. McKimmie, Beliefs about error rates and human judgment in forensic science, Forensic Sci. Int. 297 (2019) 138–147.
[28] B.L. Garrett, Wrongful convictions, Annu. Rev. Criminol. 3 (1) (2020) 245–259.
[29] G.S. Cooper, V. Meterko, Cognitive bias research in forensic science: a systematic review, Forensic Sci. Int. 297 (2019) 35–46.
[30] S.S. Hal, Statistical issues in forensic science, Annu. Rev. Stat. Appl. 4 (1) (2017) 225–244.
[31] J.L. Mnookin, The uncertain future of forensic science, Daedalus 147 (4) (2018) 99–118.
[32] C. Champod, Research focused mainly on bias will paralyse forensic science, Sci. Justice 54 (2) (2014) 107–109.
[33] M.M. Houck, Backlogs are a dynamic system, not a warehousing problem, Forensic Sci. Int. Synerg. 2 (2020) 317–324.
[34] H. Eldridge, Juror comprehension of forensic expert testimony: a literature review and gap analysis, Forensic Sci. Int. Synerg. 1 (2019) 24–34.
[35] C. Roux, O. Ribaux, F. Crispino, Forensic science 2020 – the end of the crossroads? Aust. J. Forensic Sci. 50 (6) (2018) 607–618.
[36] G. Edmond, A. Towler, B. Growns, G. Ribeiro, B. Found, D. White, K. Ballantyne, R.A. Searston, M.B. Thompson, J.M. Tangen, R.I. Kemp, K. Martire, Thinking forensics: cognitive science for forensic practitioners, Sci. Justice 57 (2) (2017) 144–154.
[37] M.M. Houck, Intellectual infrastructure: a modest critique of forensic science, Sci. Justice 53 (1) (2013) 1.
[38] C. Lawless, Organizing and supplying forensic science services, in: G. Bruinsma, D. Weisburd (Eds.), Encyclopedia of Criminology and Criminal Justice, Springer New York, New York, NY, 2014, pp. 3397–3408.
[39] S. Baechler, M. Morelato, S. Gittelson, S. Walsh, P. Margot, C. Roux, O. Ribaux, Breaking the barriers between intelligence, investigation and evaluation: a continuous approach to define the contribution and scope of forensic science, Forensic Sci. Int. 309 (2020) 110213.
[40] G. Jackson, S. Jones, G. Booth, C. Champod, I.W. Evett, The nature of forensic science opinion—a possible framework to guide thinking and practicce in investigation and in court proceedings, Sci. Justice 46 (1) (2006) 33–44.
[41] J.H. Ratcliffe, Intelligence-led policing: anticipating risk and influencing action, Criminal Intelligence for the 21st Century, IALEIA, 2011.
[42] S. Bitzer, Forensic case coordination in Europe — their role within 5 European institutes, Forensic Sci. Int. 300 (2019) 1–5.
[43] P. Margot, Traceology, the bedrock of forensic science and its associated semantics, in The Routledge International Handbook of Forensic Intelligence and Criminology, (2017).
[44] C. Champod, Forensic laboratories: is it all about survival? Polic. A J. Policy Pract. 13 (1) (2017) 47–54.
[45] Đ. Hazard, P. Margot, Forensic science culture, in: G. Bruinsma, D. Weisburd (Eds.), Encyclopedia of Criminology and Criminal Justice, Springer New York, New York, NY, 2014, pp. 1782–1795.
[46] D. Stoney, A medical model for criminalistics education, J. Forensic Sci. 33 (4) (1988) 1086–1094.
[47] O. Ribaux, Forensic intelligence and crime analysis, Probab. Law Risk 2 (2) (2003) 47–60.
[48] J.A. Siordia, Epidemiology and clinical features of COVID-19: a review of current literature, J. Clin. Virol. 127 (2020) 104357.
[49] K.A. McBride, F. Ogbo, A. Page, Epidemiology, in Handbook of Research Methods in Health Social Sciences, (2019). p. 559–579.
[50] F. Crispino, Nature and place of crime scene management within forensic sciences, Sci. Justice 48 (1) (2008) 24–28.
[51] O. Ribaux, S. Caneppele, Forensic intelligence, The Routledge International Handbook of Forensic Intelligence and Criminology, Routledge, 2017.
[52] S. Bitzer, O. Ribaux, N. Albertini, O. Delémont, To analyse a trace or not? Evaluating the decision-making process in the criminal investigation, Forensic Sci. Int. 262 (2016) 1–10.
[53] O. Ribaux, Police scientifique - Le renseignement par la trace, Collections Sciences Forensiques, Presses Polytechniques et Universitaires Romandes, Lausanne, 2014.
[54] C.E. Cleland, Historical science, experimental science, and the scientific method, Geology 29 (11) (2001) 987–990.
[55] European Network of Forensic Science Institutes, ENFSI guideline for evaluative reporting in forensic science - strengthening the Evaluation of Forensic Results across Europe (STEOFRAE). European project HOME/2010/ISEC/MO/4000001759, (2010).
[56] National Institute of Forensic Science Australia New Zealand, An introductory guide to evaluative reporting, (2017). 〈https://www.anzpaa.org.au/forensic-science/our-work/projects/evaluative-reporting〉.
[57] C. Champod, Research focused mainly on bias will paralyse forensic science, Sci. Justice 54 (2) (2014) 107–109.
[58] S.S. Birring, A. Spinou, How best to measure cough clinically, Curr. Opin. Pharmacol. 22 (2015) 37–40.
[59] T. Bendinger, N. Plunkett, Measurement in pain medicine, BJA Educ. 16 (9) (2016) 310–315.
[60] F.H.R. Vincent, Inquiry into the circumstances that led to the conviction of Mr. Farah Abdulkadir Jama, Victorian Governement, Melbourne, 2010.
[61] Forensic Science Regulator Guidance, Cognitive Bias EffectsRelevant to Forensic Science Examinations. FSR-G-217, (2020). 〈https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/510147/217_FSR-G-217_Cognitive_bias_appendix.pdf〉.
[62] O. Ribaux, A. Baylon, E. Lock, O. Delémont, C. Roux, C. Zingg, P. Margot, Intelligence-led crime scene processing. Part II: intelligence and crime scence examination, Forensic Sci. Int. 199 (2010) 63–71.
[63] O. Ribaux, A. Baylon, C. Roux, O. Delémont, E. Lock, C. Zingg, P. Margot, Intelligence-led crime scene processing. Part I: forensic intelligence, Forensic Sci. Int. 195 (2010) 10–16.
[64] O. Ribaux, P. Margot, Case based reasoning in criminal intelligence using forensic case data, Sci. Justice 43 (3) (2003) 135–143.
[65] S. Rainville, J.K. Thompson, E.G. Myers, J.M. Brown, M.S. Dewey, E.G. Kessler, R.D. Deslattes, H.G. Börner, M. Jentschel, P. Mutti, D.E. Pritchard, A direct test of $E = mc^2$, Nature 438 (7071) (2005) 1096–1097.
[66] C.E. Cleland, V.R. Baker, Common cause explanation and the search for a smoking gun, Rethinking the Fabric of Geology, Geological Society of America, 2013, p. 0.
[67] C.E. Cleland, Methodological and epistemic differences between historical science and experimental science, Philos. Sci. 69 (3) (2002) 447–451.
[68] C.E. Cleland, Prediction and explanation in historical natural science, Br. J. Philos. Sci. 62 (3) (2011) 551–582.
[69] P. Buzzini, B.W. Kammrath, P. De Forest, Trace evidence? The term trace from adjective to noun, Wiley Interdiscip. Rev. Forensic Sci. 1 (5) (2019) e1342.
[70] L.W. Alvarez, W. Alvarez, F. Asaro, H.V. Michel, Extraterrestrial cause for the cretaceous-tertiary extinction, Science 208 (4448) (1980) 1095–1108.