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Crime reconstruction and the role of trace materials from crime scene to court

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ABSTRACT

Crime reconstruction takes place in a complex ecosystem and needs to be responsive to the context of each case. For accurate, reproducible and transparent crime reconstructions to take place, a holistic approach is needed that considers the different stakeholders, different types of trace material, integral human decision making and interconnected nature of the forensic science process. For robust reconstruction there needs to be a consideration of both the distinctive types of trace material that can contribute to the reconstruction, and an understanding of the interplay of human decision making within reconstruction approaches. In addition, it is also necessary to consider source attribution of a trace material in addition to the activities that led to the generation, identification, transfer, and persistence of the trace. This requires explicit and tacit forms of knowledge, and an incorporation of the inherent uncertainty and risk in the reconstruction approach. The communication of conclusions reached in a crime reconstruction that address what the evidence means is also an important consideration given the different requirements of intelligence and evidence. Therefore, undertaking a crime reconstruction within a holistic framework that seeks to incorporate the complexity of the forensic science ecosystem is valuable for

achieving a problem solving approach that offers reproducible, transparent reconstructions with a clear articulation of risk and uncertainty that can be of value to investigators and the courts.

Graphical/Visual Abstract and Caption

Caption: Forensic science is a complex ecosystem where trace materials are vital clues. Human decision making is an integral part of every aspect of reconstruction and needs to be incorporated, with an understanding of trace materials, in the reconstruction approach.

1. INTRODUCTION

1.1 Crime reconstruction

The forensic science contribution to a crime reconstruction requires a consideration of every stage of the forensic science process (crime scene to court). It must be in synergy and dialogue with each of the major domains (science, policing, policy and law) that intersect and form the complex ecosystem within which forensic science operates (Morgan 2017a). As such, the reconstruction approach necessarily incorporates many stakeholders from each of the major domains, in addition to multiple sources of information (witness testimony, physical and digital records, forensic science evidence). When considering the forensic science contribution to the crime reconstruction approach, both the 'evidence' (physical and increasingly digital) and the human decision making that is integral to each stage of the forensic science process must be considered.

The FoRTE model (Morgan 2017a) sets out a conceptual framework for understanding this environment. It incorporates four components, which together provide an integrated overview of crime reconstruction; the forensic science process, the evidence base, the interaction of different forms of trace, and the role of expertise and human decision making (Figure 1).

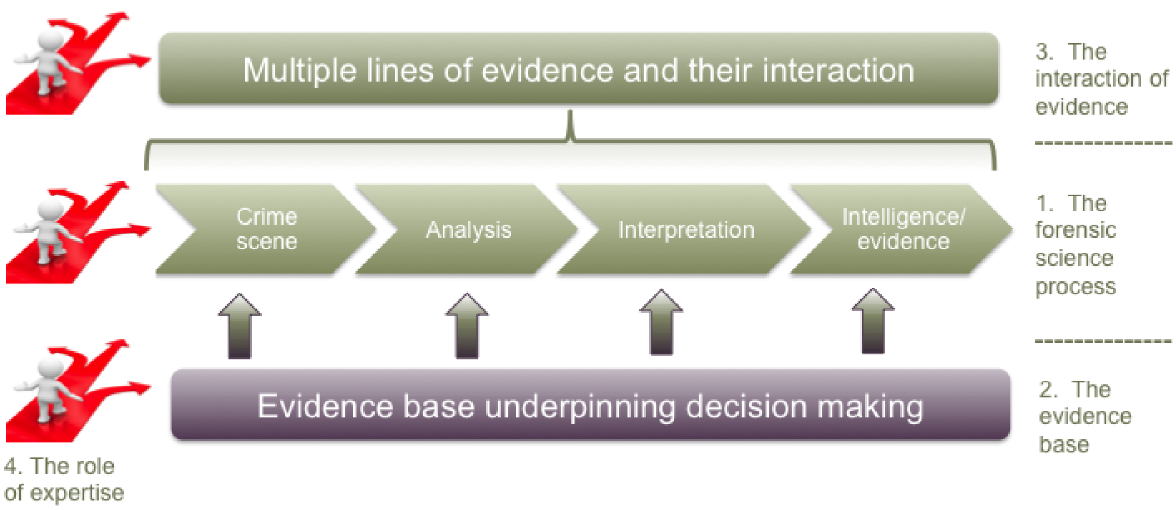

Figure 1: A conceptual model of forensic reconstruction and the role of trace materials (FoRTE) (from Morgan 2017a).

The type and nature of trace material (physical or digital; directly individualising and non-directly individualising) and the elements and circumstances of the specific case (such as eye witness testimony, CCTV footage, contemporaneous records etc) will introduce different requirements in terms of best practice for identifying, recovering, collecting, preserving, examining, documenting, analysing and interpreting those materials. For robust problem solving reconstruction approaches and to develop a problem solving approach (the 'scientific endeavour' (Roux *et al*. 2012)) that can address the case as a whole, it is important to be sensitive to the context of each case and to incorporate the range of different forms of knowledge derived from both empirical evidence bases and expertise when considering the trace material.

Reconstruction approaches must also consider the multiple institutions and individual actors within those institutions that are necessarily embedded within this process. At the institutional level, there are different approaches to knowledge acquisition, retention and communication (Morgan 2017b). The intrinsic relationships and channels of communication, which are needed between the different types of institutions (policing, law, science, policy etc.), together form an environment within which reconstruction takes place. However, this is a complex environment, not least because within different institutions there are different approaches to acquiring and communicating knowledge, in addition to different cultures, drivers, pressures, and measures of 'success'. Therefore, transparency is a highly prized attribute in reconstruction; transparency in terms of the critical question(s) being addressed (Cook *et al*. 1998a), the knowns and unknowns within the evidence base (Morgan *et al*. 2014a), and the decision pathways and evidence incorporated into the inferences and conclusions reached (Fenton *et al*. 2016; Smit *et al*. 2016).

1.2 Trace materials

Trace evidence has been the subject of significant scrutiny in recent years (The National Academy of Sciences 2009, Government Chief Scientific Adviser 2015, President's Council of Advisors on Science and Technology (PCAST) 2016, The Forensic Science Regulator 2017) and, in some jurisdictions, certain forms of trace materials have been considered to be less of a priority, despite the value they can have in a problem solving approach to reconstruction (Stoney & Stoney 2015, van Oorschot *et al*. 2019). Trace materials have the potential to offer valuable insights when the complexity of those trace materials is acknowledged. Trace materials are dynamic and variable in terms of the different forms they take, their capabilities in reconstruction approaches (in terms of source, activity and offence level attributions, directly/non-directly individualising qualities), as well as the ways that trace materials can interact with each other in a specific case (Morgan 2017a). They are also complex because human decision making is integral to evaluating what that trace means in a specific case context (Dror 2018).

Trace materials can be considered within a tripartite classification of biological traces (to include DNA), physical traces (often particulate traces such as environmental indicators (minerals, diatoms, pollen spores), glass, fibres), and chemical traces (such as elemental signatures of explosives and other forms such as fragrance). An appreciation of the dynamics of these different forms of trace material (as originally articulated by Chisum & Turvey (2000) and outlined in Figure 2) is crucial to the value trace materials can offer reconstruction approaches (The Forensic Science Regulator 2017). To evaluate the evidential weight and significance of a trace material in a crime reconstruction, it is important to understand the mechanisms of how a specific trace is generated (how that trace is separated from its parent material so that it can be transferred and deposited), how it is transferred, under what conditions it persists and is prevalent in an environment, and thus where it is likely to be recovered. A consideration of these dynamics is important for a particular trace in a specific case. However, it is also important at a more generalisable level, so that broad trends can be identified and applied to different types of traces in different scenarios.

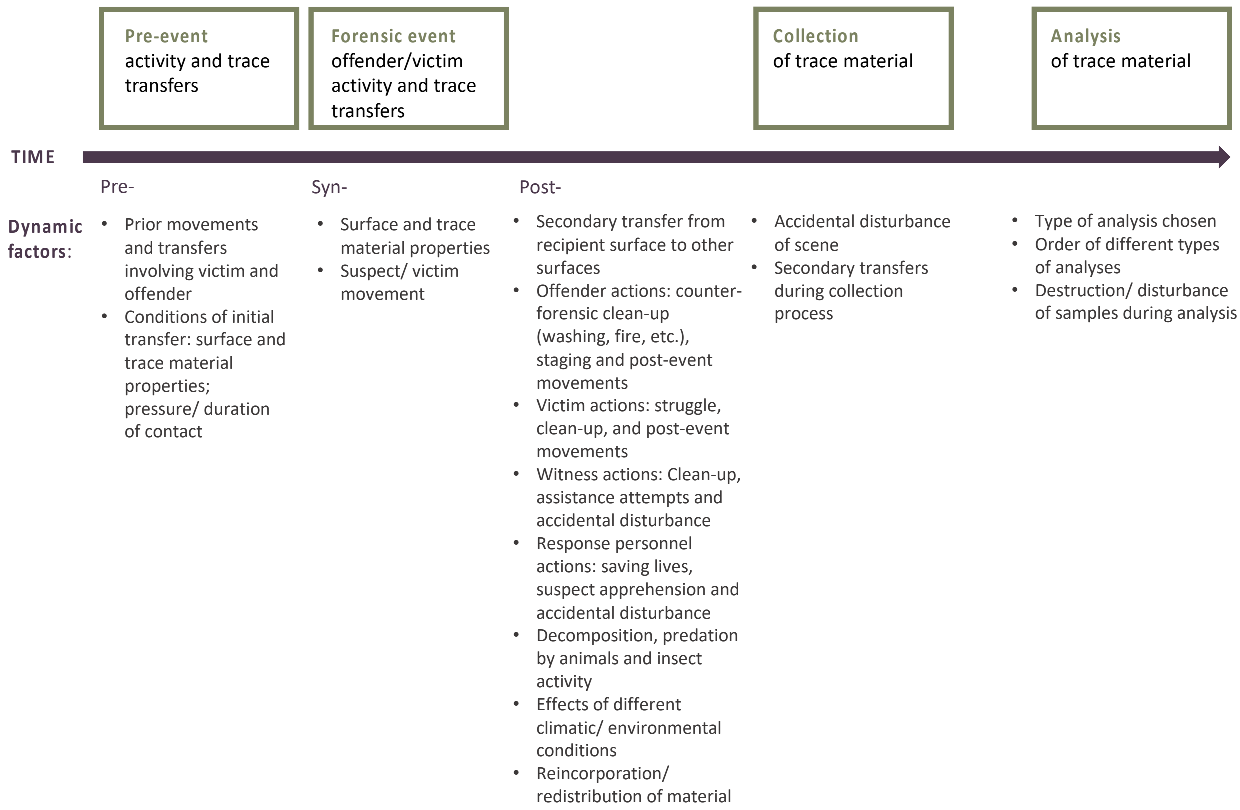

Figure 2 Key factors when considering the interaction of trace materials with the environment pre-, syn- and post-crime event (adapted from Chisum & Turvey 2000; Chisum & Turvey 2007).

This review outlines how an understanding of the complexity of the forensic science ecosystem and taking a holistic approach to the interconnected stages of the forensic science process should inform every step of a crime reconstruction. Developing reconstruction approaches that provide transparency to each of those steps, and ensure that the process is reproducible and accurate, whilst clearly articulating the risk and uncertainty inherent in any scientific approach, is critical to providing evidence-based, robust intelligence and evidence.

2. WHAT CAN WE KNOW?

To achieve a robust reconstruction, it is important to understand the dynamics of trace materials (how they come to be traces, how and when they transfer, and under what conditions), and how that knowledge interacts with the different stages of the forensic science process (Figure 1) and with different stakeholders in the forensic science ecosystem who have distinct requirements and drivers. In so doing, it is then possible to develop robust frameworks that enable transparent decisions to be made and conclusions reached as to what a trace means in a specific context.

2.1 Complex ecosystem of forensic science and reconstruction

Forensic science operates within a complex matrix that is set within the context of the intersecting requirements of different contributory stakeholders (science, practice, law and policy) (Morgan 2017b). This matrix consists of different processes (authentication, identification, classification, evaluation to achieve reconstruction) and activities (survey, preservation, examination, documentation, analysis, integration, and interpretation) (OSAC 2018), which operate within the overarching framework of holistic, evidence-based crime reconstructions (Figure 1).

Within each stakeholder environment, process and activity, knowledge is articulated explicitly (knowledge that can be codified, abstracted and is considered to be easier to communicate) or more tacitly (knowledge that is less easy to articulate and codify, and often learnt by doing) (Polanyi 1968). To achieve a holistic approach to reconstruction it is important to incorporate and utilise knowledge across the explicit/tacit spectrum to address the different types of questions that need to be answered (Morgan 2017b). For example, crime reconstructions are rarely only a matter of needing to identify what a trace material is (usually by assessing what a specimen is composed of through explicit codified standard operating procedures) to attribute its source or provenance. In order to provide an evaluative interpretation of that trace material, it is usually necessary to include an understanding of how that material was transferred, when it was transferred, and whether that was by direct or indirect means. That understanding may require the incorporation of both an empirical evidence base that supports an understanding of the mechanics of how a specific trace can transfer in a given scenario (attributes of explicit knowledge), along with the acquired expertise of the scientist that develops with experience and training (attributes of tacit and explicit knowledge).

Therefore, reconstruction must also incorporate a consideration of the decision making that is integral to each stage of the forensic science process, as well as within the stakeholder environments at the corporate and individual level. Decision making is affected by both extrinsic (often environmental) and intrinsic factors, and therefore, transparent and robust decision making requires more than codified standard operating procedures. In all the embedded decisions that need to be articulated and communicated in a reconstruction (from crime scene to court), both explicit and tacit forms of knowledge (standard operating procedures, expertise, experience, heuristics, and routines) will be important (Morgan 2017b). Therefore, current work is beginning to address the best approaches for disclosing the questions posed, assessing the hypotheses tested and the case information that is known and unknown in the reconstruction approach, in order to provide as much transparency to the process as possible (Almazourei *et al*. 2019).

However, the inherent uncertainty that necessarily exists within science, and therefore forensic science, is not something that can be removed from the reconstruction process. Whilst there is a growing body of knowledge and a specific forensic science evidence base that can underpin the reconstruction process, there are always going to be 'known unknowns' and 'unknown unknowns'. Thus, the value of developing the means of communicating uncertainty and risk is critical to effective reconstruction approaches. This is not something that a narrow application of statistics can address fully. Simple solutions to complex challenges can rarely provide the whole answer. Crime reconstructions take place in a complex matrix that is dynamic and constantly developing and changing. Therefore, it is important to incorporate uncertainty in a transparent and reproducible way within reconstruction approaches and in the way conclusions are reached, communicated and presented.

2.2 A framework for interpretation in reconstruction

One broadly accepted approach to providing transparency in how judgements are made and decisions are reached in the reconstruction process is the Case Assessment and Interpretation (CAI) framework originally proposed by Cook *et al*. (1998b). The process of reconstruction may involve identifying the trace material in question (determining its source) and it may also be concerned with attempting to understand the conditions that led to its presence at a crime scene. The value of trace materials to the reconstruction will depend on a number of factors, including analytical capability of instrumentation, the availability of data, and the nature of the question that the forensic scientist has been asked to address in a particular case (Morgan 2017a).

The CAI framework (Cook *et al.* 1998b and Jackson *et al.* 2015) provides a basis for conducting forensic examinations, and a model for communicating the results of those forensic examinations. Central to the model for CAI is the process of formulating a pair of competing propositions against which evidence is evaluated using a likelihood ratio as the basis for providing an opinion (Schaapveld *et al.* 2019). Each set of propositions can be considered within the 'hierarchy of propositions' (Cook *et al*. 1998a) to distinguish between different 'levels' of proposition ('Source', 'Activity' and 'Offence') against which trace evidence may be evaluated as outlined in Table 1.

Table 1: The hierarchy of propositions (adapted from Cook *et al*. 1998a)

Proposition	Definition	Example
I Source	The identification of the source of a trace (eg glass, body fluid, fibres etc.)	The glass fragments came from window X They came from some other broken glass object
II Activity	The assessment of how a recovered trace material was deposited or transferred.	Mr A is the man who smashed window X Mr A was not present when window X was smashed
III Offence	The assessment of the conditions that led to a deposition or transfer that corresponds to the offence itself	Mr A committed the burglary Another person committed the burglary

The level at which the evidence is evaluated will depend on the nature of the investigation and the issue that the forensic scientist is required to address. Importantly, it will also depend on the availability of relevant data, knowledge and expertise that can inform the weighing of observed evidence against propositions relating to its source or the activities responsible for its presence.

At the source level, the weighing of evidence under a pair of propositions involves the chemical, biological or physical analysis of the trace material and needs to refer to data relating to the occurrence of the same features or traits in other sources of trace material (Cook *et al.* 1998). At the activity level, the process of assigning probabilities under each proposition involves a consideration of issues associated with transfer and persistence; the expected quantities of trace material given certain transfer conditions and case-specific timeframes. In addition, data and knowledge relating to environmental or occupational sources of trace material need to be incorporated when addressing issues at this level (Cook *et al.* 1998b).

Published data, derived from experimental investigations and background surveys, represent an important part of the 'knowledge base' that is available to the forensic scientist when framing propositions, assigning probabilities and interpreting evidence in context. Examples include conducting background studies for the presence of glass (see Coulson *et al*. 2001 and Jackson *et al.* 2013) and fibres (see Jones & Coyle 2011; Wiggins & Drummond 2005), and studies addressing the transfer and persistence in relation to inorganic gunshot residue (see French *et al*. 2014 and Lindsay *et al.* 2011) and trace DNA (see Szkuta *et al.* 2017; van Oorschot *et al.* 2014). However, in many instances there is a lack of relevant data that can be relied upon to generate probability estimates, particularly in relation to activity level issues. Indeed, the generation and publication of data to support evaluative interpretation has been identified as a priority for forensic science research in successive annual reports from the UK Forensic Science Regulator (2017) and the House of Lords Science and Technology Select Committee (2019).

Therefore, the hierarchy of propositions offers a broadly acknowledged framework to organise the levels of issues that can be addressed in crime reconstruction. However, it can also provide a structure for the production of data that are needed to support the reconstruction process. The process of framing particular pairs of propositions can highlight current gaps in the evidence base, and identify pertinent deficiencies in available and applicable data, which can then be a driver for the collection of data from experimental studies and simulations, or population studies. The development of evidence bases that include data to support interpretation at the source and activity level is crucial to realising the reconstructive value of trace materials (Morgan 2017a) and addresses the calls that have been made for the development of a 'research culture' in forensic science (Mnookin *et al.* 2011).

3. UNDERSTANDING TRACE MATERIALS

3.1 Overview

To understand trace materials and to undertake robust and transparent crime reconstructions, it is important to acknowledge the complexity that is inherent to this task. Trace materials not only take different forms and therefore have different 'capabilities' in different contexts (Morgan 2017a), but they are also dynamic (Figure 2) and subject to a wide range of variables related to the environment and the type of crime and associated activities. There are a number of general traits of trace materials that are relevant to the forensic science process and therefore, crime reconstructions - trace materials are all generated, transfer, persist/are preserved, collected, analysed and interpreted (Figure 1). However, in order to illustrate the distinctive nature of different trace material types (with their distinct challenges and advantages), we present here examples of the important considerations for (broadly defined) biological, physical and chemical trace materials (as outlined in section 1.2).

3.2 Biological traces: Body fluids and DNA

3.2.1 Identification

Body fluids have traditionally been detected using tests such as luminol or the Kastle-Meyer test to detect blood, alternative light sources or the acid phosphatase test to detect seminal fluid, and the Phadebase® test for detecting saliva. However, although these tests are useful in helping to locate an area of interest for further investigation, they are presumptive tests that only indicate the possible presence of a body fluid, as the tests have many limitations, such as not being human-specific and reacting with other substances to give false positives (reviewed in Harbison & Fleming 2016). Instead, confirmatory tests are required, such as the microscopic examination of semen stains to visibly identify the presence of spermatozoa. In recent years, RNA-based technologies and epigenetic approaches have been investigated for body fluid identification, with mRNA-based assays taking the lead and being used in casework in the Netherlands and New Zealand (e.g. Lindenberg *et al.* 2013).

Body fluids are often also sampled to generate DNA evidence. When no visible or detectable stain is present, it may still be possible to recover DNA from biological material present, known as 'trace DNA' (Meakin & Jamieson 2013). There is a range of DNA analyses that can be employed, which depend on the case type and identifying what would be most informative for crime reconstruction, including routine STR (short tandem repeat) profiling, Y-STR profiling, mitochondrial DNA analysis, and the use of massive parallel sequencing for more discriminating DNA sequence analysis and/or predicting physical characteristics (e.g. hair, eye and skin colour).

3.2.2 Transfer and persistence

As with other kinds of trace evidence, biological material can be deposited by direct or indirect transfer. Whilst it is clear how body fluids, such as blood and semen, can be directly transferred to a surface, trace DNA is more complicated, as it can be transferred directly via touch or activities within the vicinity of the surface, such as speaking and coughing (Meakin & Jamieson 2013). If deposited by touch, the amount of DNA transferred depends on a variety of factors, such as the nature of the surface, the manner of contact and how well the person 'sheds' their DNA (van Oorschot *et al.* 2019). After biological material is deposited onto an initial surface, its onward transfer from that surface to another also depends on the nature of the surfaces involved and the manner of contact between those surfaces. Other variables also impact indirect transfer, such as the nature of the biological material (e.g. blood and saliva will transfer at different rates compared to trace DNA) and how dry the material is (e.g. wet blood transfers more readily than dry blood) (van Oorschot *et al.* 2019). Similarly, how long DNA persists on a surface is dependent on a range of factors, including the amount of material initially transferred, time between deposit and recovery, and what has happened to the surface in the meantime, such as being used or cleaned (van Oorschot *et al.* 2019).

3.2.3 Prevalence and recovery

When considering DNA in crime reconstruction, it is important to note that surfaces are likely to have some DNA on them prior to the event of the crime; even areas of a body, particularly hands, will have a proportion of foreign DNA present. More research is required to understand the prevalence of DNA on surfaces commonly encountered in criminal investigations and to help distinguish between this background DNA and DNA deposited at the time of the crime. In some situations, it may be useful to sample an area immediately adjacent to the area of interest to provide information on the background DNA present that could help inform activity level interpretation (van Oorschot *et al.* 2019). Sampling of a surface for DNA can be done through direct excision of a stain or via a range of methods, such as various swabs and adhesive tapes; the choice of which commonly depends on the nature of the biological material and the substrate being sampled. Recent research is starting to consider whether the choice of recovery method and/or sampling location on an item might also assist activity level interpretation of DNA, such as attempting to distinguish between different users/wearers of an item (Meakin *et al*. 2018; van Oorschot *et al.* 2014).

3.2.4 Value and challenges within forensic casework

As evidence in its own right, the identification of body fluids can be extremely valuable in crime reconstruction. For example, the identification and interpretation of bloodstain patterns can inform reconstruction of a violent event, and the observation of number of spermatozoa on a high vaginal swab can be used to infer time since sexual intercourse. Considerations of transfer, persistence, prevalence and recovery (TPPR) of body fluids can also be informative for activity level interpretation, for example when considering the timing of an event with regards to how quickly a particular bloodstain may have dried.

Using biological material as a source of DNA evidence revolutionised crime reconstruction, given its value for both the identification of offenders and exoneration of the innocent (van Oorschot *et al.* 2019). In its heyday, when DNA could be confidently attributed to a particular body fluid, source level interpretation was straight-forward. Propositions were based on whether the body fluid came from the suspect and the likelihood ratio was generated from comparing DNA profiles. However, increased sensitivity of DNA profiling technology has complicated attribution of DNA to body fluids, especially when mixtures of biological material and/or DNA are involved (Peel & Gill 2004). Consequently, source level interpretation of DNA evidence now relates to whether the DNA came from the body fluid in question and sub-source level interpretation considers whether the DNA came from the suspect or some unknown person (Evett *et al.* 2002, Taylor *et al.* 2014). For such source level interpretation, more research is required to inform body fluid attribution, although in certain cases, particularly those of sexual assault, body fluid identification using mRNA analysis can be informative. For sub-source level interpretation of DNA, it is becoming routine for probabilistic genotyping software programmes to be used to determine the likelihood ratio, although these can bring their own issues (Coble & Bright 2019).

As with other types of trace evidence, activity level interpretation of the finding of DNA is required for crime reconstruction and needs consideration of TPPR, increased research to generate the required data from empirical studies, and a database to facilitate sharing of these data (Kokshorn *et al.* 2018; van Oorschot *et al.* 2019). Furthermore, such interpretation of DNA requires recognition as a distinct area of expertise from that associated with sub-source and source level interpretation (van Oorschot *et al.* 2019), and further research and discussion to establish how best to use DNA data (e.g. quantities and/or profile information) to inform such interpretation.

3.3 Physical traces

3.3.1 Generation

Physical traces (as defined in section 1.2) are generally considered to be those that can be identified by optical methods such as microscopy. Such traces often have morphologically distinct characteristics and include hair and fibres, fragments such as glass and paint, as well as particles that include environmental materials, such as minerals, pollen grains and diatoms. The generation of physical traces is dependent on the type of trace and ranges from natural 'shedding' mechanisms (such as hairs from an animal or human, or fibres from a garment) to active disassociation from the 'parent' material (such as glass fragments from a smashed window pane, the release of minerals from a parent rock through weathering and erosion, or the production of spores from plants). How these forms of trace are generated will impact on their presence and relative frequencies within the environment. For example, mineral grains are relatively abundant in environments where soil and sediments are present (Ruffell and McKinley 2006), and certain types of pollen will be relatively abundant at certain times of year (Montali *et al.* 2006*)* or in specific locations (Mildenhall 2006).

3.3.2 Transfer and persistence

As outlined in section 1.2, understanding how physical traces interact with the physical and human environment is critical for identifying where traces are likely to be present and under what circumstances, which is important for the reconstruction of events. Empirical studies addressing the transfer and persistence of trace materials have developed since the early work of Pounds & Smalldon (1975) (fibres), Brewster *et al.* (1985) and Hicks *et al.* (1996) (glass), and Morgan *et al.* (2009) and Bull *et al.* (2006) (general particulates). There is now a growing body of published work that addresses a wide range of different physical traces (Bitter 2017 (smoke residues), Maitre *et al.* 2018 (GSRs), Palmer *et al.* 2017 and Slot *et al.* 2017 (fibres), Levin *et al.* 2017 (diatoms), Morgan *et al.* 2019 (soils) Morgan *et al.* 2014a and Morgan *et al.* 2014b (pollen)).

One form of physical trace that is gaining increased attention is diatoms. Diatoms are unicellular algae that are highly environmentally specific, and can therefore provide valuable intelligence and evidence when comparing samples to establish whether it is possible to exclude a common source (Scott *et al.* 2017). Recent studies have addressed the conditions of diatom transfer onto clothing (Scott *et al.* 2019) and footwear (Levin *et al.* 2017) and identified that the transfer of diatom valves to clothing depends on the fabric type (Scott *et al.* 2019). Even brief contact with footwear can lead to the transfer of diatoms, with valves persisting for up to 168 hours under some conditions (Levin *et al.* 2017).

There has also been a growing interest in the use of fluorescent proxies for trace particulates since the original work of Bull *et al.* (2006). Developments in this area have been gaining momentum as imaging technologies have increased in their capacity to process digital images, alongside the development of increasingly accessible automated approaches in image analysis (Levin *et al.* 2018). These developments are increasing the size of data sets for transfer and persistence that can be produced in reasonable time frames, and are thereby growing the evidence base that can inform our understanding of trace dynamics in casework relevant situations.

3.3.3 Analysis

Physical trace material is often analysed in a comparative manner with a relevant sample recovered from an exhibit being compared to a sample taken from a known location, such as a crime scene or an alibi site. For example, with environmental traces, such as minerals or diatoms, it is relatively common when specimens are recovered from exhibits, such as footwear or vehicles, that those specimens are often composed of materials from multiple sources that may represent locations visited pre- or post-crime event (Morgan *et al.* 2019). One of the benefits of 'physical' (particulate) trace materials is that, during the analysis phase, it is possible to identify components (usually optically) from multiple sources that are present within a sample (Morgan & Bull 2007a). Being able to compare a mixed source sample (for example from an item of footwear) to a single source sample (for example from the crime scene) and reduce the risk of false negatives is a valuable attribute (as outlined by Morgan & Bull 2006). To date, attempts to apply analytical techniques that require the homogenisation of a sample of trace material prior to analysis, in order to distinguish between different sources of material present in a single sample, have only served to demonstrate the complexity of the task (for example for mixed source DNA samples (Butler *et al.* 2018) and in the elemental (chemical) discrimination of soil samples (Cheshire *et al.* 2016)). This remains a significant challenge for these analytical methods.

3.3.4 Value and challenges within forensic casework

In addition to being able to identify components within a sample from different original sources (as outlined in section 3.3.3), physical traces are also valuable for comparative analysis of samples from known and unknown locations. Within an exclusionary framework that seeks to identify differences between samples (Morgan & Bull 2007b), it is possible to offer valuable exclusionary inferences and intelligence to investigators and sometimes evidence to a court (Morgan & Bull 2006).

Whilst 'physical' forms of trace can offer exclusionary inferences at 'source' level, inferences regarding the activities that may have resulted in their transfer is an area that is currently being addressed more fully in the published literature. One area that is particularly relevant to environmental forms of physical evidence is the ability to gain insights into when a transfer may have taken place due to the seasonality of some forms of environmental materials, such as pollen and diatoms. It has been shown that diatom communities are seasonal in their abundance (Round 1984), and as a result the diversity of a diatom assemblage (species richness) is greater when a transfer occurs in the spring in comparison to other times of year (Scott *et al.* 2019). This attribute has been demonstrated to have been useful in casework when reconstructing events where the timing of the deposition of a key exhibit is important to establish (Cameron 2004).

Multiple transfers, often referred to as indirect or secondary (or tertiary) transfers, have been considered for physical traces in relation to understanding how and when a specific trace may have been transferred (similarly to trace DNA as outlined in section 3.2). Early studies demonstrated that secondary and tertiary transfers of traces can and do occur between people and objects (French *et al.* 2012). Developing an increased understanding of when this can happen, and in what quantities, is an important area of enquiry for physical traces (as well as trace materials more widely), given the clear impact that understanding the nature of these transfers has when reconstructing the order and timing of events in a reconstruction.

There is, therefore, great value in undertaking experimental studies and simulations that can offer insights into the quantities of trace that can transfer during certain types of direct and indirect contact. There is also a need to develop more empirical insights into the nature of a trace that is transferred during a specific type of contact (for example, the size of diatom valves transferred onto different types of footwear material and where traces are most likely to transfer to on that piece of footwear (Levin *et al.* 2017)), and the degree to which traces may be reincorporated after an initial transfer (Morgan *et al.* 2010; Stoney *et al.* 2016). Establishing the dynamics of these forms of trace materials to a greater degree will enable increasingly transparent and evidence-based reconstruction conclusions to be reached in casework scenarios.

3.4 Chemical traces

3.4.1 Generation

'Chemical trace' refers to a class of trace materials that may be analysed using a range of chemical analysis methods to detect their presence in samples taken from crime scenes. These chemical compounds may originate from chemical reactions associated with the forensic event or they may be the constituents of a trace material that are deposited on surfaces through transfer or dispersion. Like biological and physical traces, these compounds must then persist so that they can be recovered and subsequently analysed. For example, gunshot residues (GSR) are produced when firearms are discharged, and can be used to reconstruct incidents involving firearms.

Comprehensive reviews of the analysis of organic and inorganic GSR have been carried out by Meng & Caddy (1997) and by Dalby et al. (2010). The presence of inorganic GSR particles is typically determined through the non-destructive analysis and interpretation of elemental signatures and morphological features using scanning electron microscopy with energy-dispersive X-ray analysis (SEM-EDX). Other chemical traces include explosive residues and novel forms of forensic evidence, such as fragrance (Gherghel et al. 2016). The reconstructive value of these traces lies in the ability to identify the source of the trace through the comparison of its chemical composition to potential sources. Furthermore, the analysis and interpretation of the quantity and distribution of the trace can assist in making inferences about the conditions and activities that resulted in its deposition in a similar manner to physical trace materials (see section 3.3.4).

3.4.2 Transfer and Persistence

As with other types of trace, chemical traces may be transferred by direct or indirect mechanisms and may persist on surfaces or in the environment following transfer or deposition. Understanding the factors that govern rates of transfer between surfaces and rates of decay from those surfaces is crucial to realising their reconstructive potential.

Fragrances and perfumes may be identified through the analysis of their chemical constituents and can be transferred between surfaces such as clothing or human skin. In a recent study by Gherghel *et al.* (2016), the forensic value of chemical traces associated with perfume fragrances in mock casework scenarios was explored. Using GC-MS, it was demonstrated that the type and quantity of fragrance compounds transferred varied according to the dryness of the perfume at the time of the transfer and according to the length of the contact between donor and recipient surfaces during the simulated transfer events. The study found that when a transfer took place after perfume had been left to dry for five minutes following its application, 24 components of the perfume were detectable on the recipient surface. By contrast, when the perfume was left to dry for seven days before the transfer, six components were detectable. Meanwhile, increasing the contact time between the fabric swatches from five minutes to ten minutes resulted in an increase in the number of detectable perfume components on the recipient surface (from 16 to 18) (Gherghel *et al.* 2016). These data may be used to support inferences in the temporal reconstruction of incidents that have involved contact between a victim and an offender (ibid.). Thus, data on expected levels of transfer and persistence can inform the process of recovering chemical traces at the crime scene.

The recovery and analysis of GSR may enable the scientist to identify an ammunition source. However, beyond source level questions, the presence of GSR can enable us to reconstruct other aspects of an incident such as shooting distance and direction (Glattstein *et al.* 2000), time since discharge (Jalanti *et al.* 1999) and the identification of the shooter (French *et al*. 2014). The ability to make robust and accurate inferences relies on an understanding of the behaviour of GSR and the factors affecting its deposition, transfer and persistence (see Blakey *et al.* 2018 for a recent review). GSR is deposited on surfaces in the vicinity of the firearm discharge which may include the hands, face and clothing of the shooter. It has been found that the initial quantity of GSR that is deposited on the shooter can vary greatly between firings (Matricardi and Kilty 1977). Meanwhile, French *et al.* (2014) and French & Morgan (2015) used mock transfer scenarios to demonstrate that GSR particles originating from firing a self-loading handgun could be transferred to the hands of non-shooters through secondary and tertiary transfer mechanisms via the shooter or via a 'dirty' firearm. It has also been shown that GSR particles may be deposited on individuals in the vicinity of the firearm discharge (Lindsay *et al.* 2011) and that particles are lost rapidly from the hands of shooters in the first two to four hours after discharge (Jalanti *et al.* 1999). An appreciation of these dynamics and reference to these published data informs both the recovery of evidence and the process of determining the weight of evidence in casework.

3.4.3 Value and challenges in casework

The identification of chemical traces can be highly valuable in crime reconstruction. The presence of these traces may inform the reconstruction of events that involve contact with illicit materials, transfers between individuals, or the discharge of firearms or explosives. During an investigation, the process of identifying the trace and its source may be challenging for a number of reasons. For example, the existence of environmental sources of GSR-like materials should be acknowledged when attempting to determine whether or not GSR in present in a sample in order to avoid false-positive identification. Such particles may be associated with the use of stud guns (Wallace & McQuillan 1984) and in samples from car brake linings (Cardinetti *et al.* 2004; Torre *et al.* 2002), underlining the need for careful analysis and interpretation. While the proliferation of lead-free ammunition has presented new challenges for GSR identification, the possibility of introducing luminescent markers to assist the process of collection and reconstruction has been explored (Lucena *et al.* 2013, 2017).

A range of studies have addressed the identification of forensically relevant chemical traces in the environment such as illicit drugs in waste water (Castiglioni *et al.* 2014; Zuccato *et al.* 2008), explosive compounds in waste water (Gamble *et al.* 2017) and also trace explosive vapours (McEneff et al. 2018). A key issue for identifying chemical traces in these scenarios is distinguishing the signature of interest from background 'noise'. For example, some studies have sought to establish an expected level of background concentration of trace organic explosives in wastewater. In establishing the background concentrations, it is then possible to provide the means of detecting deviations from the background levels, which could represent valuable intelligence or evidence in instances involving the manufacturing or processing of explosives (Rapp-Wright *et al.* (2017)).

Establishing the source of chemical traces can be highly relevant, and often requires the consideration of possible environmental and occupational sources. For example, when considering GSR, there is the possibility of coming into contact with GSR through recreational shooting or from contaminated sources in police facilities and vehicles (Gerard *et al.* 2012). Establishing background (environmental) levels of specific traces (Royds *et al.*2005) and considering alternative sources of traces is important. In certain scenarios, this may present challenges for the interpretation of what the trace means in the context of a case with implications for the crime reconstruction.

While the transfer and persistence properties of chemical traces may present challenges for the reconstruction process, the same properties can also be harnessed in the design of security measures. One example would be SmartWater®, an organic traceable liquid that is used to mark assets and premises. As well as representing a valuable tool for crime reconstruction by increasing the possibility that offenders are apprehended after committing a crime, SmartWater® also supports the prevention of crime by deterring would-be offenders (Tilley and French 2017).

Realising the reconstructive potential of chemical traces depends on the ability to successfully detect their presence through the development and application of robust analysis methods and to distinguish these traces from other sources of similar trace. Meanwhile, the degree to which the quantity and distribution of the trace can be used to support interpretation at the activity level will depend on the availability of appropriate data on the generation, transfer and persistence of traces that may be applied to casework scenarios. As with all forms of trace material, it is clear that there is value in experimental studies that seek to establish detection limits, background concentration levels, and generate data in relation to transfer and persistence.

4. INTERPRETATION OF TRACES: THE HUMAN DIMENSION

4.1 Overview

As outlined in sections 2 and 3, there has been an increased awareness of the importance of acknowledging the complexity of trace materials that may be recovered from crime scenes (Margot 2011; Roux *et al.* 2012). This has led to calls to focus on developing approaches to effectively interpret what a trace means, which incorporate an empirical evidence base and the context specific nature of a particular scene (Morgan & Bull 2007b). There may be similarities between forensic investigations, yet the context of an individual crime scene will be specific to that particular event. It is therefore important to incorporate a holistic understanding of each crime event that integrates considerations of how a specific trace may have been generated, how and when it was transferred (Morgan *et al.* 2018a; Roux *et al.* 2015), and how it may have been preserved, in order to inform the best approach for the collection and analysis of a trace to inform the interpretation of what it means in a specific case and draw evaluative conclusions (Morgan 2017a, Morgan 2017b).

The context sensitive nature of each forensic case also makes incorporating an understanding of human judgement and decision making highly important (Morgan 2017a). Decision making is an integral and dynamic part of the forensic science process because humans are critical in the classification, identification and management of materials within the process, in addition to interpreting results from sensitive and accurate analytical techniques. There is therefore a need to integrate an understanding of human decision making into every stage of the forensic science process (Figure 1) in order to achieve increasingly reproducible and transparent reconstructions (Earwaker *et al.* 2019, Morgan *et al.* 2018b).

However, there is inherent uncertainty present in much of the decision making taking place in the reconstruction process (e.g. Dror 2018, Dror & Langenburg 2019). Although the role of human interpretation in this process is critical at every stage, it is a multifaceted attribute due to the very nature of human decision making, where cognitive and psychological factors have the potential to affect how information is gathered, processed and retrieved (Dror 2016; Edmond *et al.* 2017).

4.2 Human decision making in crime reconstructions

4.2.1 Human cognition and decision making

It is well established within the field of psychology that human perception and cognition are affected by context, motivation, expectation and experience (Koehler & Harvey 2004, Gilovich *et al*. 2002). The human mind has limited capacity for information processing and therefore relies heavily on prior experiences, beliefs, emotions and knowledge when encoding information (Hoppitt *et al*. 2010, Dror 2011). This causes the human cognition process to be very selective, using cognitive "shortcuts" in order to process large amounts of information. Although this processing operates automatically and is extremely beneficial (allowing for decision making to be quicker and more accurate), paradoxically, it has also been shown to be the source of what is known as cognitive bias causing (at times) judgment and decision making to be unreliable (e.g. Evans & Pollard 1990; Nickerson 1998; Nisbett & Ross 1980). This has been particularly notable when decisions are being made under conditions of uncertainty (e.g. Edmond *et al*. 2015; Kahneman & Tversky 2013; MacLean & Dror 2016).

In the past decade, the body of research addressing the effects of environmental factors (or attributes of the stimulus or the situation) on expert decision making has grown, with the findings showing that context is influential in how people construct, seek, and interpret information (Balcetis & Dunning 2006; Edmond *et al*. 2017; Saks *et al.* 2003). In forensic science, there has been a growth of empirical research studies addressing context effects within forensic interpretations (Found 2014). Many fields of forensic science include subjective assessment and comparison stages that have the potential to be susceptible to the effects of cognitive bias due to their reliance on human judgment (Kassin *et al.* 2013; Thompson & Cole 2007). The growing concern over expert decision making being influenced by cognitive processes has led to a growth in research specifically focusing on applying different judgment and decision making theories within crime reconstruction approaches (Edmond *et al.* 2017; Found 2014). It has been demonstrated that these vulnerabilities are not limited to a specific field, with similar interpretation issues being highlighted across a wide range of forensic science domains (Dror *et al.* 2006; Dror & Hampikian 2011; Miller 1984; Nakhaeizadeh *et al.* 2014; Osborne *et al.* 2016, Stoel *et al.* 2014).

4.2.2 Judgement and decision making in crime reconstruction

Interpretation of trace materials can be (in certain circumstances) challenging. Traces are complex due to their variable nature, for example they can be degraded (e.g. partial, mixed or poorly resolved) resulting in a level of ambiguity inherent within the trace itself (Edmond *et al.* 2015). Much of the research and debate within the literature in interpretation and cognitive biases in forensic science has traditionally been focused within the identification fields (e.g. Dror *et al.* 2006). Trace evidence studies have been mainly concerned with source attribution and the interpretation issues that have been identified when assessing partial and mixed DNA profiles (e.g Butler 2005; Butler *et al.* 2018; Dror & Hampikian 2011; Jeanguenat *et al.* 2017; Krane *et al*. 2008, Paoletti *et al.* 2005; Thompson 2009). An empirical study that assessed contextual effects in the interpretation of mixed DNA samples showed that the interpretation of the examiners differed depending on the case context (Dror & Hampikian 2011). The result from this study showed that when the DNA mixture (taken from an adjudicated criminal case) was presented to 17 neutral DNA examiners (with no contextual information or case background provided), only one expert agreed with the original examination.

Further, as outlined in several models on the forensic science process (e.g. Inman & Rudin 2002, Morgan & Bull 2008, Ribaux & Talbot Wright 2014), the decisions made at a crime scene will impact upon what questions are being asked with regards to the exhibits and specimens, what analysis to undertake in the laboratory, as well as the approaches to draw conclusions and interpretations of the results generated (Morgan 2017a). A recent study into crime scene examination and the effect of context information on the search for and selection of traces, showed that contextual information impacted the first impression of the scene and the crime scene behaviour of the investigator, ultimately affecting the search strategy and the selection of trace material subsequently secured (van der Eden 2019). Therefore, understanding the human decision making process at early stages and including a holistic approach to human interpretation throughout the process are vital for reconstructing crime events. If the decisions about what to collect at the crime scene have been influenced by misleading information or irrelevant context, it has been demonstrated that this could cascade and create interpretative difficulties at a later stage (Dror et al. 2017, Nakhaeizadeh et al. 2018).

Some of the methods used in crime reconstructions have been criticised on the basis of their questioned validity (Law Commission 2011; National Academy of Sciences 2009; Mnookin 2018; President's Council of Advisors on Science and Technology 2016), and for being improperly applied, with the misapplication of forensic science currently debated as a contributing factor in wrongful convictions (Garrett & Neufeld 2009). Although a recent study from the U.S. has highlighted that a very low percentage in wrongful conviction reports cited forensic science as the sole contributor to wrongful convictions (La Porte 2017), caution in interpretations when dealing with complex and limited data has been called for (e.g. Dror & Langenburg 2019). In addition, a recent study highlighted that the majority of misleading evidence types in cases upheld at the Court of Appeal in England and Wales related to the interpretations made concerning activity level propositions (Smit *et al.* 2018). To be able to infer the significance of a trace when it is found in a particular location at a particular time, an understanding of the dynamics of these forms of trace is essential (Figure 2), in addition to understanding where the assumptions are being made (French & Morgan 2015), and what could influence those assumptions (see section 2). Therefore, in crime reconstruction, human interpretation is important for not only establishing the source of a trace and the activity level that may have led to the deposition of a specific trace, but also for making inferences about what the trace means and the evidential weight and significance of the trace in a specific case context (Margot 2011; Morgan 2017a; Roux *et al.* 2012).

4.2.3 Addressing the impact of context

There is a growing consensus in the forensic science community with respect to contextual effects, and how to minimise the risk they pose in reconstructions. The most common solution proposed is separating the analyst from contextual information that has no relevance to the scientific process (Almazrouei *et al.* 2019; Dror 2013), in addition to adopting a case manager model, and separating various laboratory functions by assigning them to different people (e.g. Saks *et al.* 2003, Thompson 2011). In laboratories, linear sequential unmasking has been suggested as a hybrid approach to minimise the potential for contextual bias where for example, a known DNA profile might affect the interpretation of an evidence sample (Dror 2016; Risinger *et al.* 2002). However, finding an appropriate balance between the risk and benefits of enacting solutions that seek to deal with the issues of contextual effects is not an easy undertaking, due to the complexities of the decision making involved in crime reconstructions, the inherent biases, and the different stakeholders and institutions, which all have different institutional frameworks and different drivers (Morgan 2017b). Therefore, embracing a constructive discussion about the role of human decision making, how it aids the crime reconstruction process and where there are intrinsic limitations and uncertainties is important. Given that biases are inherent to decision making, it is important that reconstruction approaches are developed that offer transparency in how inferences and conclusions are reached, and how they are communicated (to investigators, to a court) so it is clear what extrinsic and intrinsic factors may have had a bearing on a conclusion that has been reached.

As a community, it is important to foster a transparent and sustainable culture of human decision making in forensic interpretations. This culture needs to be based on incorporating a holistic approach that fully explores decision making within the forensic process, identifying where issues exist, and finding ways in which decision making processes can be more transparent and in some cases developed to ensure the delivery of a robust crime reconstruction approach (Morgan 2017b).

5. CONCLUSIONS

Crime reconstruction needs to be undertaken with a holistic understanding of the complex ecosystem of forensic science (Figure 1). It is necessary to develop a clear understanding of the nature of trace materials (their generation, transfer, persistence, prevalence, recovery (Figure 2)) and the judgement and decision making that is integral to each stage of the forensic science process (Figure 1) to make inferences about what intelligence trace materials can offer, be transparent about how conclusions are reached, and thereby offer a robust, transparent and reproducible reconstruction.

Identification of a trace is an important first step, but in order to understand what the trace material means in a given context, it is important to be mindful of the need to establish both source and activity level inferences with reference to the appropriate evidence bases that incorporate both explicit and tacit knowledge. It is also necessary to acknowledge the intrinsic nature of human decision making in each component crime reconstruction (Figure 1) and therefore the importance of a good understanding of how inferences are made and conclusions are reached in a manner that is sensitive to the context of a reconstruction.

It is also important to develop approaches that can incorporate transparency into how we communicate the meaning of evidence, and the ultimate crime reconstruction, and that sufficiently convey inherent uncertainty and risk. Forensic science rarely has situations where it is possible to establish a 'ground truth', and therefore the way that we communicate the meaning of trace evidence and how we consider the reliability of a crime reconstruction is very important. A consideration of inherent uncertainty also has implications for how quality, reliability, reproducibility (and therefore 'error') of the constituent activities, analyses and decision making that contribute to a reconstruction are assessed. Therefore, the evaluative interpretation of evidence at the activity level is increasingly being recognised as a distinct area of expertise (van Oorschot *et al.* 2019) that is needed across the whole domain of trace evidence. As a result, it is clear that in crime reconstructions both explicit and tacit forms of knowledge should be valued, considered and incorporated into the reconstruction process (Morgan 2017b).

Complex environments require a nuanced approach to address the key challenges in forensic reconstruction. Acknowledging the complexity of the forensic science ecosystem (that addresses the different actors, institutions, circumstances, types of material (and potential evidence) at every stage of the forensic science process) is the path to achieving context sensitive crime reconstructions with a problem solving approach (Roux *et al.* 2012) in a way that offers transparency and clarity, and acknowledges the requirements of the different stakeholders (Morgan 2018b).

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