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The Complexity of Evidence-Based Forensic Interpretation

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I, Michaela Regan, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

Abstract

The 2009 NAS report (US) and the 2011 Law commission report (UK) highlighted concerns within forensic science and presented the need for evidence bases to underpin the interpretation of forensic evidence. Such evidence bases are critical for forensic science to demonstrate the basis upon which the significance of evidence is inferred. However, this has instigated a lively debate concerning the use of experimental studies as a means of providing more robust, reproducible and empirical based interpretation of forensic evidence. Thus, the aim of this thesis was to explore the need to improve communication between forensic scientists and lawyers due to the complexity of implementing an evidence base in forensic science. This research sought to gain insight into: (1) the degree to which experimental studies concerning evidence dynamics of trace particles such as gunshot residue (GSR) can assist in the interpretation of activity level reconstruction and (2) the receptivity of lawyers and forensic scientists to the use of experimental studies.

A series of experimental studies addressing the deposition, persistence and analysis of GSR identified that there is value in performing experimental studies to understand the information that can or cannot be inferred from the evidence. As a result, there is a need for clear communication of forensic findings by forensic scientists and criminal lawyers to ensure that the interpretation of forensic evidence in court is as transparent as possible.

Questionnaire responses provided insight into the perspective of criminal lawyers and forensic scientists on the use of experimental studies to underpin interpretation. The findings indicated that most forensic scientists and criminal lawyers do not tend to use the published literature to support evidence interpretation. This highlights a need to ensure that research is available to both forensic scientists and criminal lawyers in a format that is accessible and pertinent to their requirements. Increasing channels of communication and enabling collaboration between forensic scientists and criminal lawyers is therefore highly desirable for ensuring the interpretation of forensic evidence in court incorporates empirical findings.

Both studies indicate that there are significant complexities for implementing evidence-based interpretation. There is therefore a need to improve the lines of communication between criminal lawyers and forensic scientists to ensure that (1) research is more forensically relevant and thus useful and (2) evidence is placed under sufficient scrutiny in court by having the different stakeholders have a clear understanding of the findings.

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Chapter 1: Introduction

1.1 Introduction

In 2009, the National Academy of Sciences (NAS) released a report criticising the lack of scientific underpinning across the forensic disciplines (National Research Council, 2009). These criticisms have been further reiterated in subsequent documents like the 2016 PCAST report and the 2011 Law Commission report (Chief Scientific Advisor, 2015; Executive Office of the President President's Council of Advisors on Science and Technology, 2016; Law Commisson, 2002; Forensic Science Regulator, 2016). It has been argued that these reports have highlighted the lack of systematic evidence base that is required to validate techniques and underpin the interpretation of evidence (Saks & Faigman, 2008; Saks & Koehler, 2008). This means that there does not currently exist a published and systematic evidence base to support forensic conclusions and so practitioners must rely on experience to interpret results instead. To provide robust forensic interpretation, evidence-based decision making is important to have at all stages of the forensic science process. Thus, there is an urgent need to undertake research on the different forensic disciplines to establish an evidence base to support practitioners' inferences and conclusions about the weight and significance of forensic evidence (McElhone et al. 2016).

Empirical studies of this kind would underpin evidence based scene management, sample collection, analysis, interpretation and presentation of evidence. Such research is especially important for the different types of evidence where establishing the way the evidence will deposit, transfer and persist has been more difficult (Brożek-Mucha, 2011a; French et al. 2014; Gerard et al. 2011). For instance, research into gunshot residue has highlighted the complexity of interpreting the meaning behind detecting a GSR particle as it has been shown to be so variable that accurate interpretation is not often possible (Charles & Geusens, 2012; French & Morgan, 2015; Patterson, 2014). As a result, its use has been discontinued by the FBI and other crime laboratories in the United States (Patterson, 2014). This is exacerbated as empirical studies into the behaviour of GSR cannot identify any patterns to its behaviour (Cardinetti et al. 2004; Fojtášek et al. 2003) nor place much value on the amount of GSR found under different circumstances because it is currently not possible to obtain samples with known amounts of GSR (Shaw, 2016; Dalby et al. 2010).

Further, even though research is already on-going to address the scientific underpinning in forensic science, there is no cohesion on this research (Silverman, 2011). That is, there is a lack of research culture in forensic science where there is little communication and collaboration between forensic science practitioners, academics and lawyers (Mnookin et al. 2010). Communication between these stakeholders is particularly important when conveying interpretations on more complex forms of evidence such as GSR. This lack of communication causes problems such as duplication which hinders forensic science progress as time is spent repeating research instead of building on that research (House of Commons, 2005). This is also partly because of the limitation in research dissemination (Chief Scientific Officer, 2015; Silverman, 2011). For instance, research is published in academic journals which forensic science practitioners and lawyers may not have access to. Additionally, research is written in scientific terms which can be complicated for the non-scientific audience (such as lawyers and judges) (Cashman & Henning, 2012; Edmond, 2013). Thus, a research culture is needed in forensic science to address the gaps in research to implement an evidence base. In sum, this limits the impact of the research and prevents it from forming a comprehensive literature.

However, not everyone in the scientific community has agreed that this evidence base and additional research is necessary (Edmond, 2003; Koehler & Meixner, 2016). As a result, there is an on-going debate as to whether interpretation should be based on empirical studies or professional experience (Edmond et al. 2016). This debate hinders the progress of implementing an evidence base because, without undertaking the relevant research, the findings presented to the courts remain questionable. Therefore, there is a need to address this debate so that the concerns raised by the NAS report can be addressed. Thus, considering the intricacy of the forensic science research landscape and the mixed receptivity of performing empirical studies, the aim of this thesis is to explore the need to improve communication between forensic scientists and lawyers due to the complexity of implementing an evidence base in forensic science.

1.2 Research Questions

To address this aim, the thesis will look into (1) the use of experimental studies to improve interpretation of evidence and (2) the perspective of forensic scientists and criminal lawyers on the need for evidence-based interpretation. The use of experimental studies will be investigated to demonstrate what information can be interpreted, whilst also considering situations when robust interpretation may not be possible. As a result, exploring this area will highlight the need to communicate and ensure all parties understand the weight of forensic findings. Additionally, the perspectives of forensic scientists and lawyers on the use of professional experience and experimental studies to provide robust interpretation of evidence will be explored because even though policymakers have urged for additional research, there is a need to come to a consensus on the best approach forward. Gaining additional insight into these two areas will help identify key recommendations on how to improve on communication and collaboration on casework and research which can assist with implementing an evidence-based approach in forensic science.

Thus, this thesis will address the following questions:

1) What is the impact that additional research can have on forensic interpretation and can such research assist with interpreting complex forms of evidence such as GSR?
2) How much consideration has been given by forensic scientists and criminal lawyers on research evidence as a foundation on which to make forensic decisions?
3) In the light of the findings of questions 1 and 2, what are the key recommendations to the forensic science community to improve communication between forensic scientists and criminal lawyers on casework and on research?

1.3 Outline/structure of the thesis

This thesis is structured as follows. In chapter 2, a substantive literature review is presented, then chapters 3 and 4 consist of two experimental chapters and chapter 5 is a discussion chapter with key recommendations for casework and research. The thesis then concludes with chapter 6 which provides a summary of the findings and the final conclusions that have been reached.

More specifically, chapter 2 is composed of a substantive literature review. It identifies that a substantial amount of research has been undertaken investigating the effect that different variables have on trace evidence. In particular, it identifies that such empirical studies have assisted in generating a clearer understanding on the transfer and persistence of fibres, pollen and soil. However, these studies have also identified the complexity of interpreting the presence of gunshot residue (GSR). This complexity has led to the discontinued use of GSR by the Federal Bureau of Investigation (FBI) and other crime laboratories in the United States. Thus, there is a need to undertake additional research to further understand the way GSR behaves under different circumstances and to assess the value of GSR as an item of evidence. As such, the literature review considers the role experimental studies can play in establishing an evidence base, and discusses the current state of the forensic science research landscape and the hindrances facing the forensic science community that are inhibiting the cohesion of such research.

Chapter 3 examines the transfer, persistence and analysis of GSR to demonstrate the complexity of performing experimental studies. This chapter consists of three experimental studies. The first study examines the distribution of GSR on clothing of bystanders and is divided into two parts. The first part investigates whether there is a pattern to the distribution of GSR based on the standing arrangement of three bystanders in relation to the shooter. The second part looks into the distribution of GSR on the clothing of a bystander standing behind a shooter and a bystander standing to the right of the shooter. The second study then investigates the persistence of GSR on three bystanders over a 12-hour period. The last study analyses the complexity of establishing a screening tool for GSR in situ by using p-XRF (portable X-Ray fluorescence) as an example. These studies highlight the complexity of performing empirical studies on GSR and emphasise whether additional research can provide the scientific foundation needed in forensic science. The fieldwork was undertaken at Cranfield University in collaboration with Dr. James Shackel and the shooting range staff. The presence and absence studies were analysed at UCL and the quantitative analysis was partially undertaken at Staffordshire University and partially at the Forensic Science Service in Adelaide, Australia. The results were then analysed using SPSS in collaboration with Michael Frith (UCL Security and Crime Science).

Chapter 4 explores the perspective of forensic scientists and lawyers on their use of the published literature and case-based experimental studies. This was undertaken by disseminating a survey to forensic scientists and criminal lawyers to gain insight into their perspectives on the use of published literature for forensic interpretation, the use of case-based studies and the communication and collaboration between these stakeholders. The results were then analysed using SPSS in collaboration with Michael Frith (UCL Security and Crime Science).

Chapter 5 reviews the two experimental chapters (chapter 3 and 4) and the published literature (chapter 2). This chapter highlights the need for improved communication within the forensic science community and in particular between forensic scientists, policymakers and criminal lawyers. It summarises that this communication is vital in improving casework and research and is the first step towards achieving an evidence base in forensic science. This chapter will review communication in these two areas and provide recommendations for further improvement to open the lines of communication between forensic practitioners, academics and criminal lawyers. This thesis focused on opening the lines of communication rather than methods of communication. As such, concepts such as (1) Bayesian networks to assist with demonstrating the strength of evidence and (2) bias to understand decision-making remain out of the remit of this project and thus have not been explored further.

In chapter 6, this thesis will conclude that there is a need to improve on communication and collaboration between forensic scientists and criminal lawyers on research and casework.

Suggestions to opening these lines of communication vary from initial consultations, additional face-to-face meeting and standardising of forensic science reports.

Chapter 2: Literature Review

The introduction briefly discusses the release of the NAS report and the effect this report has had on the forensic science community. However, to understand this effect, it is imperative to understand the changes that have occurred since then to address the lack of scientific underpinning in forensic science. Therefore, this chapter reviews the published literature to evaluate the forensic science process and understand the complexity of evidence interpretation. It will then continue to discuss the NAS report and the role of experimental studies in addressing the lack of scientific underpinning in forensic science. This will be illustrated by using GSR as a prime example of where additional research is needed to provide more robust interpretation. Lastly, it will look at the debate on the use of experimental studies or professional experience as the basis for interpreting evidence, and the effect this debate has had on casework and research.

2.1 The forensic process

Before conducting research in any forensic field, it is important to understand the forensic process. This process includes the order of events from the collection of evidence at the crime scene, to its analysis in the laboratory, to its presentation in court. Looking at the order of events demonstrates the importance of avoiding contamination and maintaining the integrity of the evidence throughout this process. Additionally, it shows the complexity of interpreting evidence and presenting the results in court.

2.1.1 Conceptual framework

It is important to consider the order of events to demonstrate the individual steps that occur within a forensic investigation (see Figure 1, Morgan & Bull, 2007; Morgan et al. 2008). All forensic investigations are dependent on the occurrence of step one to three: it is only possible to analyse physical evidence (step 4) if the material has been divided, transferred from the source material (step 1), and persisted long enough after its creation (step 2) to be properly collected (step 3) by following the appropriate procedures.

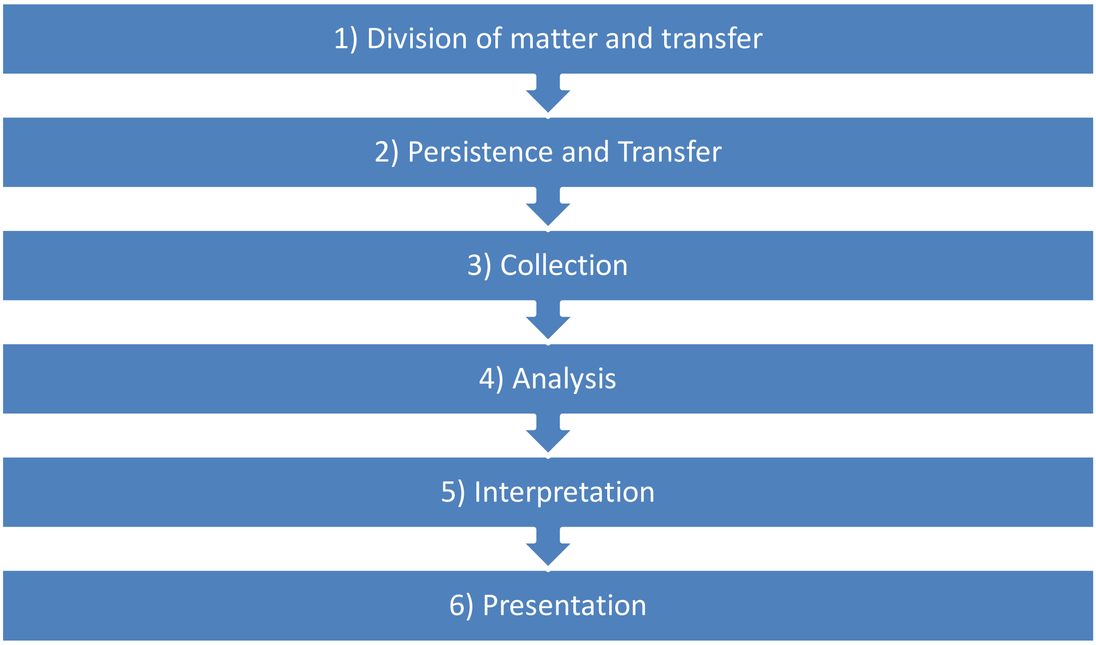


Figure 1. The forensic process illustrating each individual step from the generation of evidence to the presentation in court

After the collection of evidence, appropriate analysis must be performed to provide accurate interpretation (step 5) of the findings which are later presented to the court (step 6). If incorrect handling of the item of evidence occurs at any stage, it will impact the later stages and can affect the integrity of the evidence or the accuracy of the results. Therefore, care needs to be taken at every stage to allow evidence to assist an investigation to its fullest potential.

The forensic process highlights the importance of performing further experimental studies for each individual step to understand how different items of evidence behave under different circumstances. For instance, a better understanding of what items of evidence are generated under particular scenarios will assist the collection of evidence. This will provide experts with insight into the different types of evidence that might be present at the scene, and the likelihood of finding them in a particular state. Additionally, experimental studies on the analysis stage will ensure that the most up-to-date techniques are used. Further, these studies will assist with the interpretation of the results in court by having a better understanding on the effect of different variables on the transfer and persistence of evidence. Lastly, it will also provide information on the likelihood of finding a particular item under a particular circumstance and therefore assist with assessing the weight of the findings (i.e. the presentation of evidence in court).

2.1.2 The integrity of evidence

To understand the factors that affect the item of physical evidence, it is important to understand the influences that affected the item both pre-and post-discovery during any criminal investigation. For instance, variables that influence an item pre-discovery need to be understood to determine the most suitable approach to the collection, analysis and thus the interpretation of evidence. Post-discovery, it is important to recognise these factors in order to understand the actions which need to be taken to prevent contamination, and to maintain the integrity of the item (Cosic & Baca, 2010; Wisconsin State Crime Laboratories, 2009).

Before the discovery, determining every influence that the evidence has been exposed to is impossible. However, it is feasible to get an idea of the influences present at the crime scene to minimise these unknowns and to determine the effect they might have had on the item (Chisum, 2006). Thus, there is a need to gain further information on the evidence dynamics. The term evidence dynamics refers to "any *influence that can add, change, relocate, obscure, contaminate, or obliterate physical evidence, regardless of intent"* (Chisum, 2006). By understanding the evidence dynamics, it is possible to see the effect these influences can have upon the transfer and persistence of an item. For instance, it is common for an item of evidence to be generated in one area and discovered at another (Chisum, 2006). When this is the case, the influences that affect the transfer and persistence of evidence need to be considered when interpreting what the evidence means.

Once the item has been discovered, it needs to be protected from external influences to maintain its integrity (Murphy, 2007; Cosic & Baca, 2010). This is important because if the evidence has been improperly collected, handled or stored, its value may be destroyed and no amount of laboratory work will be of assistance (Wisconsin State Crime Laboratories, 2009). To demonstrate an item's integrity, a chain of custody needs to be maintained to provide a chronological documentation of every person who has come into contact or handled the evidence (Evans & Stagner, 2003; Wisconsin State Crime Laboratories, 2009). This chain starts the moment an item is located and continues throughout its custody, transfer, and analysis to allow for a controlled setting throughout the forensic process (see Figure 1, steps 3-5). This chain is often closely scrutinised, causing the evidence to be challenged, and sometimes rejected, due to improper handling or documentation. For that reason, every step taken throughout the forensic process needs to be accounted for to demonstrate that the integrity of the item has been maintained.

2.1.3 Interpretation of evidence

The forensic expert is responsible for presenting the court with an objective interpretation of the physical evidence based on observations, test results and measurements (Karagiozis & Sgaglio, 2005). However, the interpretation of evidence is hindered by only being viewed as a single individual step of the forensic process and therefore only occurring once the analysis has been completed. Whereas, realistically, the interpretation of evidence is an on-going process which should occur throughout the duration of a case, from the moment the expert views the evidence until the presentation of the findings in court (Saks & Koehler, 2008).

2.1.3.1 The case assessment and interpretation (CAI) model

To assist with interpreting evidence, the Forensic Science Society (FSS) presented the Case Assessment and Interpretation (CAI) model (Jackson and Jones, 2009; Cook et al. 1998b). Its aim was to improve the communication between the investigating officers and the forensic scientists to allow the forensic analysis to assist the investigation to its fullest. The CAI model is divided into three stages:

1) Customer requirement: the investigating officer and the forensic expert discuss the needs of the investigative officer and the questions that they would like the forensic expert to try and answer.
2) Case assessment: the expert evaluates the information at their disposal to determine which analyses are possible and would enable them to answer the desired questions.
3) Service delivery: the samples have been analysed and the conclusions are presented in the form of a report to the investigative officer.

These three stages act as a framework to assist with objective decision-making based on scientific results to provide the investigating officer with the required information.

2.1.3.2 Hierarchy of propositions

An important part of the model, and of any interpretation, is to weigh a pair of propositions against each other (Biedermann et al. 2012; Cook, Evett et al. 1998a). In other words, it is often the case that the defence and the prosecution will each present a hypothesis to explain how a certain type of evidence might have been left at the crime scene. After which, it is the duty of the forensic expert to determine which hypothesis is more likely to have occurred (Evett et al. 2002). For instance, if a fingerprint is found on an object at the scene, that does not necessarily mean that the person was present during the crime. So, the prosecution and the defence each provide an explanation to how the fingerprint might have been deposited on that object. After which, the forensic expert looks at the evidence that was found and the case information to determine which pair of propositions can be addressed (Biedermann & Taroni, 2012; Foreman et al. 2003). To address the hypotheses presented, it is helpful to consider a "hierarchy of propositions" which looks at three different levels of analysis: the source, the activity and the offence level (Figure 2, Cook et al. 1998a).

Figure 2. The hierarchy of propositions demonstrating the three individual levels: source, activity and offence

The source level addresses whether an item of evidence can be associated to a specific source (Figure 2) i.e., "Did the glass fragments come from the broken window?" (Biedermann & Taroni, 2012; Foreman et al. 2003; Cook et al. 1998a). For many years, experts were associating evidence to a particular source due to the 'uniqueness' of a pattern or mark left on an item (Saks & Koehler, 2008; Cole, 2009). However, the term "uniqueness" can be misleading, as it is not always possible to associate an item to only one specific source, excluding all others (Budowle et al. 2000). For instance, the scientific comparison of two paint chips, one recovered at a crime scene and the other from a suspect, can determine if their chemical composition is similar, indicating whether they originate from the same brand. However, this association does not necessarily mean that the chip found on the suspect originated from the scene (Cwiklik, 1999). Cole et al. (2009) suggested that rather than using the phrase "uniqueness", it is best to deduce the most likely source through the exclusion of all other possible sources. By doing so, such confusion can be avoided and a more accurate representation of the results is provided.

The activity level addresses whether a person can be associated to an action (Figure 2, Cook et al. 1998a; Jackson et al. 2006) i.e. "is Mr. A the man who smashed the window?". This level is more complicated because the expert needs to consider the possibility of evidential transfer and persistence. So, to consider these variables, it may be more accurate to ask: "What is the probability Mr A. smashed the window considering the amount of glass fragments found on the clothing?" To address such questions, the expert needs further case information, such as how the window was smashed, and the timeframe between the incident and the sampling of the clothing. This background information can assist with determining whether there are extenuating circumstances which may explain the presence of these glass fragments (Cook et al. 1998a; Morgan et al. 2009). Thus, a thorough understanding of the context of the case may change the significance of finding the physical evidence that was involved in the crime.

The offence level is where it needs to be determined whether the 'activity' can be considered an offence (Figure 2, Cook et al. 1998a; Meuwly & Veldhuis, 2012). For instance, there is a difference between “Mr. A pushed Mr. B” and “Mr. A assaulted Mr. B”. This distinction is determined by the court and lies outside of the forensic scientists’ domain. However, the forensic expert can give an indication of which hypotheses is more likely to have occurred, which can assist the court with making this distinction.

In practice, The CAI model helps differentiate the type of information that a forensic scientist can provide to a case. However, it does not clarify the limitations of these findings. That is, a forensic scientist can identify what a sample is or where to find it. However, with the lack of scientific underpinning, it is not possible to infer meaning behind finding a particular item. Thus, without additional research, forensic scientists are limited in the information they can provide to a case or risk the chance of misinterpreting evidence.

2.1.4 Presentation of evidence in court

The difficulty with presenting evidence in court is that the jury do not tend to have a forensic background. As a result, the jury do not understand the strengths and limitations associated with the different types of forensic evidence (Karagiozis & Sgaglio, 2005). This is especially difficult because the jury can be overconfident in their forensic knowledge due to television shows such as CSI (Robbers, 2008). As such, forensic scientists are responsible for ensuring the findings are clearly presented in court, including the associated limitations. However, forensic scientists often use subjective terminology and different ways of describing their findings. For instance, some experts use the term “certainty” (e.g. very certain, quite certain) and others use the phrase “likely” (e.g. very likely, very unlikely). This is because there is no standardised format of presenting evidence in court (Edmond, 2013; Ligertwood & Edmond, 2012). This can be confusing for the jury who are hearing different ways of presenting findings (Christensen et al. 2014). However, experts might be able to provide the jurors with more guidance to assessing the weight of the findings if experimental studies were used to demonstrate to the jury that 1) the best approaches have been adhered to, and 2) the effect of the transfer and persistence of evidence has been considered when interpreting evidence (R.M. Morgan et al. 2009; M. J. Saks & Faigman, 2008; Saks & Koehler, 2008). Thus, the role of experimental studies and how these will form an evidence base needs to be clarified.

2.2 Role of Experimental studies

In forensic science, there is currently a well-established knowledge base where validated techniques and methods are drawn from other scientific fields e.g. chemistry (drug analysis) and biology (DNA analysis) (Cole, 2007). Similarly, there are some forensic techniques, such as handwriting and fingerprint comparisons, which lack a scientific foundation and therefore do not have authentic evidence of their effectiveness e.g. fingerprinting and firearm examination (Saks & Faigman, 2008). Thus, to address the lack of scientific underpinning in forensic science, the literature has been advocating for the use of evidence-based interpretation (National Research Council, 2009; Executive Office of the President President's Council of Advisors on Science and Technology, 2016; Forensic Science Regulator, 2016).

A similar situation occurred in medicine, where treatments were being performed without any evidence of their efficiency. Further, tests and treatments were being recommended based on experience, rather than on empirical studies (Greenhalgh et al. 2014). Similarly, experimental studies were performed to address these criticisms. Such studies determined the accuracy of medical techniques and were used to support the experiential knowledge of the expert. Thus, evidence-based medicine (EBM) brings together medical evidence, theory and practice (Bensing, 2000; Djulbegovic, 2017; Davidoff et al. 1995). EBM does not, however, offer a new scientific theory of medical knowledge, but instead has progressed as a coherent, heuristic structure for optimising the practice of medicine (Bensing, 2000; Davidoff et al. 1995; Greenhalgh et al. 2014). Medical science is a good analogy for forensic science, because they are both based on fact-finding by using the available evidence to determine the best approach for testing and interpreting results (Cole, 2007).

Additionally, in the last decade, policing has become more evidence-based to determine the most effective methods of reducing crime (Lum et al. 2013; Sherman, 2015). Policing research has always fallen under the social sciences category (Lum, 2009). However, in recent years a more scientific approach has been undertaken to empirically establish the effect of policing (Dawson & Williams, 2009). Policing is also a good analogy for forensic science as policing has often been considered a 'craft' and not a science, like certain types of forensic evidence such as fingerprinting (Lum & Lum, 2014). Looking at these two different areas, it can be deduced that a similar approach is needed within forensic science by developing a more coherent, robust and effective way to interpret evidence.

To establish such an evidence base in forensic science, there are three main stages (Figure 3): a primary level of experimentation, a general body of theory and a secondary level of experimentation (Morgan et al. 2009).

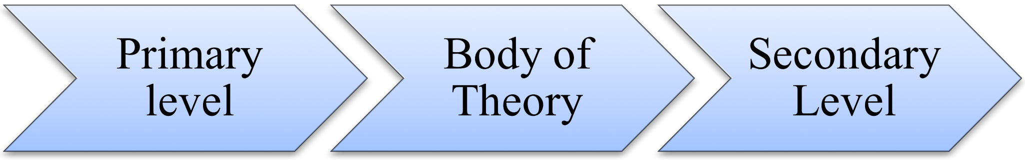


Figure 3. The three main stages to establishing an evidence base: performing the primary level of experimentation, establishing a body of theory, and performing a secondary level of experimentation

2.2.1 Primary level of experimentation

The primary level of experimentation (Figure 3) focuses on analysing the effect that general variables have on the generation, persistence and transfer of evidence (Morgan et al. 2014). Establishing the effect of these variables provides a scientific foundation for the individual types of evidence based on empirical and reproducible data (Saks & Koehler, 2008). The benefit to establishing a better scientific foundation is that, it would not only provide the expert the opportunity to test a hypothesis, but it would also demonstrate how the test was conducted to external parties. These external parties can then repeat and confirm the results for themselves (Saks & Faigman, 2008). This reproducible data will then act as confirmation for the obtained results which forensic practitioners can draw upon to demonstrate the reliability and validity of their interpretation.

Further, this primary level of experimentation enables the best procedures and protocols to be established for the collection, analysis, interpretation and presentation of evidence (Saks & Faigman, 2008; Morgan et al. 2009). This is done by gaining insight into both the behaviour of evidence and the techniques used such as the detection limits. Acknowledging the limitations of analysis is critical to accurately convey the weight of the results (Christensen et al. 2014).

2.2.2 General body of theory

The results from the primary level of experimentation can then be implemented as a general body of theory. This will act as a baseline to provide information on the general rules of behaviour for the different types of evidence (Morgan et al. 2009). However, this should only be used as a baseline because every scenario has different conditions and specific variables unique to the case. As such, secondary experimentation is needed to adapt the analysis and theories to each case (Bull et al. 2006).

2.2.3 Secondary level of experimentation

The secondary level of experimentation should occur on a case by case basis. Its aim is to recreate the crime scene to see how an item of evidence in a particular location will behave under different circumstances (Figure 3, Morgan et al. 2014). This secondary level of analysis has limited applications but will be more informed than the primary level. Additionally, these studies will take into account particular circumstances that are specific to a case to determine how a specific item of evidence behaves, in order to conduct accurate and meaningful interpretation (Morgan et al. 2009; Linacre, 2013). This secondary level provides the expert with case-specific research to support their interpretation and to strengthen their position in court (Silverman, 2011).

Such an approach goes some way towards addressing the concerns raised by the NAS report. However, interpretation of evidence can be complex as the effect of a multitude of variables need to be considered or, at times, there are unknowns that cannot be accounted for. Even though experimental studies can establish the scientific underpinning in forensic science on a primary level of experimentation, improving the interpretation for more complex forms of evidence might be more difficult to accomplish. A prime example of a complex form of evidence where further insight into its behaviour is needed is GSR.

2.3 Example of GSR

Research into the primary level of experimentation to establish an evidence base and a general body of theory has already started. Therefore, it is necessary to review these studies to demonstrate areas where further expansion is needed. GSR is a prime example, due to its decline in forensic laboratories because of the variability of GSR and the difficulty of interpreting the meaning of finding GSR at a scene or on a suspect (Patterson, 2014; Maitre et al. 2016). Additionally, this chapter will focus on GSR because it is important to solve gun crime as accurately as possible, because, in 2014/15, there were a total of 7,866 recorded firearm offences in England & Wales (House of Commons, 2016).

2.3.1 Formation of GSR

When a firearm is discharged, a chain reaction occurs causing the firing pin striking the primer cap on the base of the cartridge (Figure 4, Patterson, 2014). The compounds in the primer cap react, igniting the gunpowder present within the body of the cartridge. Once the gunpowder is ignited, a high temperature chain reaction occurs, causing the bullet to propel out of the firearm. During this reaction, combustion products from both the primer and the propellant are simultaneously released through any opening, which forms a vaporous cloud called the plume. As the temperature decreases in the plume, primer GSR is formed (Charles et al. 2011).

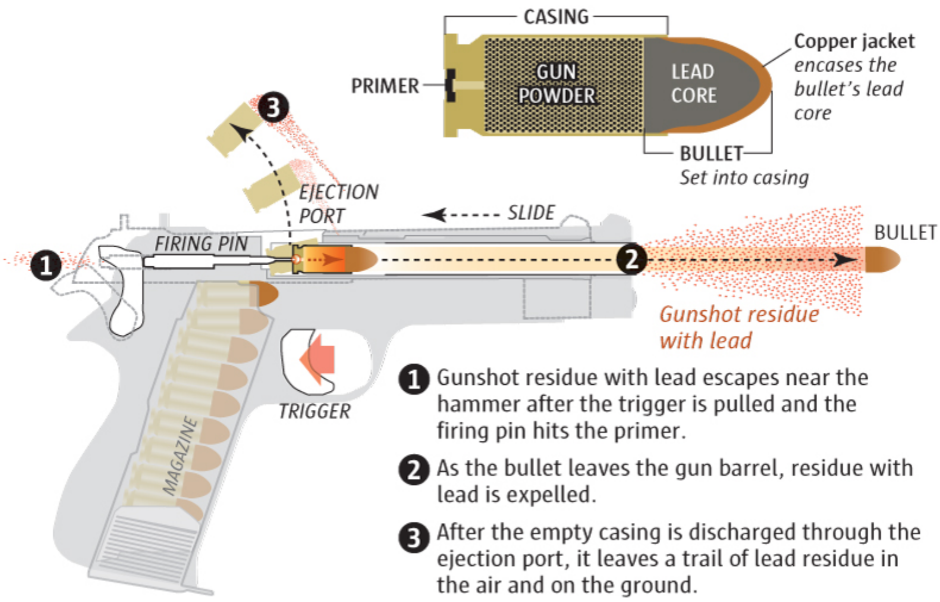


Figure 4. A diagram demonstrating the production of GSR (Willmsen et al, 2014)

Primer GSR is comprised of metal-based particulates which are generally spherical in shape and range from 0.5 to 10 µm in size (Dalby et al. 2010b; Basu, 1982) . The elemental composition of GSR particulates varies depending on the type of firearm, type of ammunition, and the cleanliness of the firearm (Bueno et al. 2013). However, the three main elements searched for in GSR are barium (nitrate), antimony (sulphide) and lead (styphenate). Three elements that do not tend to appear together in nature and are therefore considered the discriminatory part (Kara et al. 2015; DeGaetano & Siegel ,1990). However, recent studies have shown that these barium-antimony-lead aggregates can also be found from other sources such as fireworks and brake pads. As a result, the identification of GSR is easily contested in court (Garofano et al. 1999; Grima et al. 2012).

2.3.2 Classification of GSR

The classification system currently used for GSR is the 2010 American Society for Testing and Materials (ASTM) standard and is generally used by researchers and professionals (Table 1, ASTM, 2016). This entails looking for spheroid particles between 0.5 and 10 µm in diameter with a composition "characteristic of GSR" or "consistent with GSR" to have the following elemental profiles (Abrego et al. 2012):

Table 1. The 2010 ASTM classification system for GSR

Classification	Elemental composition
"characteristic' of GSR"	Pb-Ba-Sb
"consistent' with GSR"	Ba-Ca-Si Sb-Ba Pb-Sb Ba-Al Pb-Ba Pb Ba Sb

The morphology of GSR particulates can vary significantly depending on multiple factors, for example the time and the distance between the point of production to the point of impact (Abrego et al. 2012). For that reason, there have been preliminary studies to determine the effect that different variables can have on the morphology (Brożek-Mucha, 2011b; Brożek-Mucha, 2011a). For instance, it has been shown that larger particles tend to travel further during discharge (Brożek-Mucha, 2011a). However, it is unclear how the morphology differs and under which circumstances. Therefore, the morphology of the particulate is considered secondary to the elemental composition for GSR identification.

2.3.3 Investigative use of GSR

GSR is a prime example of evidence corroboration because while the presence of GSR cannot necessarily link a suspect to a particular firearm, it can indicate that a subject has been exposed to GSR in one of three ways: (Murtha & Wu, 2012; Latzel et al. 2012; Andrasko & Pettersson, 1991)

1. By detecting GSR particulates on the hands or clothing of a person to confirm whether someone has recently handled a firearm, or been in the vicinity of someone who has
2. To assist with determining firing distances
3. To analyse a bullet entrance hole

However, the absence of GSR does not exclude the possibility that an individual has recently discharged a firearm. There are several reasons why a person may not have GSR on them such as the time that may have elapsed after exposure and the activity of the individual (Patterson, 2014; Jalanti et al. 1999; Chisum, 2006). Therefore, these factors need to be considered when interpreting the presence or absence of GSR.

2.3.4 Transfer of GSR

An important variable to consider when interpreting the presence of GSR is its ability to transfer between people and objects. The potential of secondary and subsequent transfers further complicates interpreting the presence of a particular item at a particular location or on a person. Thus, it is important to not only look at direct transfer but also the nature of subsequent transfers.

2.3.4.1 Direct transfer

Direct transfer relates to a situation where evidence is transferred from a material source to a person or an object (Charles & Geusens, 2012; Jones et al. 2016; Tessarolo & Gaudette, 1987). In the case of GSR, it is released from the gun into the atmosphere depositing on the hands and clothing of the suspect, and the general vicinity. However, interpreting the presence of evidence is further complicated when the transferred material subsequently transfers.

2.3.4.2 Subsequent transfers

Subsequent transfers of evidence can be classified as a secondary transfer, tertiary, quartenary and so forth from the original primary transfer (French et al. 2014; Robertson et al. 2011; Szynkowska et al. 2013; Taupin, 1996; French et al. 2012).

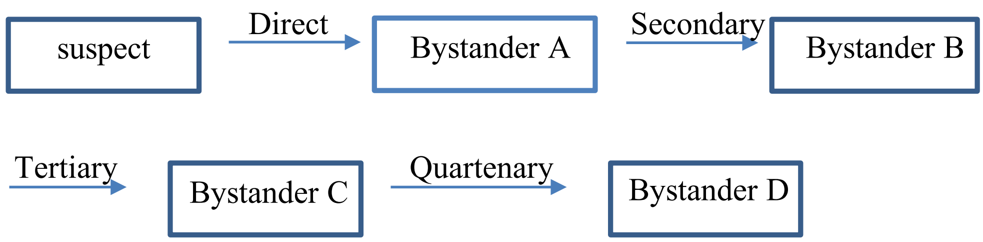


Figure 5. A diagram to illustrate the different types of transfer

A primary transfer is a direct transfer from the item of physical evidence to a suspect (Figure 5, Tessarolo & Gaudette, 1987; Taupin, 1996). A secondary transfer is an action causing a transfer between suspect A and bystander B, such as shaking hands (Figure 5, French et al. 2014). However, it has been shown that these transfers can continue from bystander B to bystander C and so on. Furthermore, secondary transfers may be influenced by various factors: they could be the amount of contacts an individual has, which would make communally handled objects more likely to have transferred material (French et al. 2012). These indirect transfers allow incriminating trace material to transfer to unconnected individuals, which would allow the material from an independent individual to be deposited at the scene (French et al. 2012). This can be either before the crime occurred or via an offender.

Subsequent transfers are shown to frequently occur with GSR. However, it has been shown that GSR particles can transfer onto the suspect from the arresting police officer or from the police car during transit (DeGaetano & Siegel, 1990; Charles & Geusens, 2012; Berk et al. 2007). For instance, it is forensic practice to test for GSR after a suspect has been apprehended, secured and transported to the police station. This is concerning because it is currently not possible to determine the precise source of the GSR and thus difficult to demonstrate how GSR was deposited on a person or a suspect. Furthermore, this leads to problems with differentiating between a shooter and a bystander based on GSR counts (Lindsay et al. 2011). For instance, French et al. (2015) performed a study where a bystander stood 1m behind a shooter whilst discharging a firearm for 5 rounds. They found that the bystander had a similar amount of GSR to the shooter. Additionally, GSR transfers occur readily through small interactions, such as the handling of a gun (Basu et al. 1997) and a handshake between a shooter and an unrelated individual (French et al. 2012). For instance, French et al. (2012) demonstrated the possibility of secondary and tertiary transfer through handshaking: they had a shooter discharge a firearm and shake hands with participant 1, who then shook hands with participant 2. Thus, these examples demonstrate the ability of GSR to transfer which highlights the need to gain further insight to determine whether the presence of GSR can be interpreted at the activity level.

2.3.5 Persistence of GSR

Persistence of GSR is important to consider for the collection phase, during the interpretation phase, and for the presentation phase of the forensic process (see Figure 1). Looking into the persistence of GSR provides a better understanding of inferring time since transfer, as well as activity level information in a crime reconstruction (Chisum, 2006). However, the limitations to persistence studies are twofold: 1) there are no guarantees that transferred particulates would be recovered and 2) the use of repeat sampling as it lessens the particulates available compromising the results (Pounds & Smalldon, 1975c). Thus, these limitations need to be considered when interpreting the results of any persistence studies

2.3.5.1 Time since transfer

Studies into the time since transfer can assist with linking a suspect to a crime scene by determining time of deposition. Additionally, such studies can assist with sampling protocols, i.e. the likelihood of still locating an item of evidence. Establishing such a timeframe has been especially difficult for GSR because the amount of GSR initially released during discharge is unknown (Kotrly & Turková, 2010). Therefore, the difference between the concentrations of GSR at different times cannot be directly compared to the original concentration. For that reason, persistence studies of GSR have been performed to determine whether or not it is still worth collecting a sample after x hours/y activity rather than to determine when the transfer of this trace was made (Dalby et al. 2010).

Studies into establishing a timeframe for GSR have had different results ranging from one hour to 48 hours on the hands (Jalanti et al. 1999; Romolo & Margot, 2001). This is due to the variations in the experimental design such as different physical activities within this timeframe and different firearms used; this affects the retention of GSR, and hence demonstrates the variability in establishing a timeframe. For instance, multiple studies have concluded that the persistence of GSR on hands, where the subject was not allowed to wash their hands for the duration of the study, can last up to 6 hours (Brożek-Mucha, 2011a; Krishnan, 1977; Jalanti et al. 1999). However, Rosenberg and Dockery (2008) noted that when participants were allowed to wash their hands that the rate of GSR was more variable and that sampling hair or clothing would be more likely to retain GSR for longer. This demonstrates the effect that influencing factors, such as physical activity, can have upon the persistence of GSR. As a result, an empirical decay curve might not be identifiable, but there is still a need to better understand how these particles shed from clothing, skin or other surfaces (Dalby et al. 2010).

Due to the complexity of establishing such a timeframe, it is current forensic practice to analyse a suspects' hands up to 4 hours after firing; their face up to 6 hours: their hair up to 12 hours; the clothing up to 24 hours of normal wear on the surface by taping and up to 48 hours of normal wear by vacuuming (Shaw, 2013). However, without an empirical platform to demonstrate the accuracy of these timeframes, it is possible that valuable evidence is going undetected. Thus, until such timeframes are better established, it is still beneficial to sample GSR regardless of the time elapsed, because previous studies have shown that GSR tends to adhere to the weave of the fabric (Patterson, 2014). The complication with sampling without an empirically established timeframe is that there is no information on whether GSR found on clothing could have come from previous exposure (Murtha & Wu, 2012). Therefore, any time lapse makes it difficult to link the suspect to the crime, and requires additional information about the subject to rule out these scenarios.

2.3.5.2 Movement of GSR particulates

When GSR is not detected on clothing, it is generally assumed that either the suspect can be excluded or that only a few particulates were transferred during contact and have all been lost due to subsequent wear (Wallace, 2008). However, another reason that particles have been overlooked is because they tend to move and embed themselves within the recipient material (Wiggins et al. 2002; Pounds & Smalldon, 1975b; Robertson, 2013; Mastruko, 2003). For instance, it has been demonstrated that particles tend to remain in the stitching and creases of clothing (Cwiklik and Taupin, 2011). This does vary depending on the type of clothing due to the coarseness of the material: the coarser material will retain more particles. For instance, a t-shirt will shed particulates more easily than jeans (Charles et al. 2013; Cwiklik and Taupin, 2011).

Furthermore, the spatial distribution of particles on clothing is often used to assist with crime reconstruction, by providing information on the possible location of a person during a crime scenario (Chisum, 2006). However, Morgan et al. (2010) have demonstrated that particles tend to reincorporate from one item of clothing to another, for example from upper garments to lower garments during normal wear. As a result, it is possible that most particles would have concentrated on the lower garment. Additionally, when evidence is individually packaged, particles tend to redistribute on the same item prior to sampling: it usually occurs after an item has been collected, packaged and transported to the laboratory (Morgan et al. 2010). As such, it will not be possible by this stage to place any value on the specific area of the clothing where particles are found for crime reconstruction.

This emphasises the need to consider the possibility of reincorporation and redistribution when sampling and interpreting the location of the trace evidence (Morgan et al. 2009; Pounds & Smalldon, 1975a; Cwiklik and Taupin, 2011). This is especially true for the interpretation of GSR as it has become increasingly difficult to differentiate a bystander from a shooter. Attempts have been made to better understand the spatial distribution of GSR: their aim was to determine whether it is possible to use the location of GSR to determine where someone was standing compared to a shooter. Studies into the spatial distribution of GSR have demonstrated a variety of results, but found that the maximum radius where GSR travels can range from 10-18 metres depending on the type of firearm used and the external environmental conditions (Gerard et al. 2011; Fojtášek et al. 2003). These studies highlight the difficulty of establishing the effect different variables have on the spatial distribution. Additionally, they demonstrate the need to perform further experimental studies, to hone in on these environmental conditions, to better understand the utility of the spatial distribution of GSR for crime reconstruction.

2.3.6 Analysis of GSR

In forensic laboratories in the UK, it is standard protocol to analyse GSR samples on a scanning electron microscope/electron dispersive x-ray spectroscopy (SEM/EDX) (Chang et al. 2013; Dalby et al. 2010a). The SEM images the morphology and size of a particle and the EDX analyses the elemental composition (Sundaram, 2015). The SEM produces high resolution images of surface topography by using a scanning (primary) electron beam (Siegel & Mirakovits, 2007). The primary electrons enter the sample surface with an energy of 0.5 – 30 kV and generates many low energy secondary electrons. The intensity of these secondary electrons is largely aimed at the surface topography of the sample. An image of the sample surface can thus be constructed by measuring secondary electron intensity as a function of the position of the scanning primary electron beam.

In addition to low energy secondary electrons, backscattered electrons and X-rays are generated by primary electron bombardment. The analysis of the X-rays emitted from the samples provides elemental information (Siegel & Mirakovits, 2007). This is because, at rest, an atom within the sample contains unexcited electrons in different electron shells bound to the nucleus. When the incident beam hits an electron in the inner shell, this electron may get excited and be ejected from the shell (Siegel & Mirakovits, 2007). This creates an electron hole and the atom becomes unstable. To stabilise the atom, an electron from an outer, higher-energy shell then drops down to fill the hole, and the difference in energy between the higher-energy shell and the lower energy shell is released in the form of an X-ray. The number and energy of the X-rays are measured by the EDX. The energies of the different X-rays are characteristic to different atoms, thus allowing the elemental composition of the specimen to be measured.

For GSR analysis, the SEM/EDX has an automated search system that analyses the samples for the presence of barium, antimony and lead. Once it has mapped these elements, the forensic expert re-analyses the positive results for confirmation (ASTM, 2016; Wallace, 2008). Without this automated software, it is possible to manually analyse samples to detect GSR. This is usually done by the analyst who searches for the appropriate size and shape of particulate and manually selects it for analysis. This process is time-consuming and less accurate than the automatic approach, as it increases the possibility of having false negatives made by particulates going undetected (Niewoehner et al. 2005). The main advantage of the SEM/EDX is that it is non-destructive, allowing for further testing to occur and it also requires minimal sample preparation. However, it takes a long time to carry out the analysis which causes delays in an investigation (Bueno & Lednev, 2014; Latzel et al. 2012; Schumacher & Barth, 2010). The lengthy searching is due to the time spent examining, analysing and rejecting a large number of non-firearms particles, and the extraneous material such as fibres and skin debris which could make the particles difficult to find or even conceal them from view (López-López & García-Ruiz, 2014). To minimise the number of samples being analysed, a screening tool could potentially be applied in a forensic context to assist with identifying GSR at the crime scene (Janssen et al. 2015). Such a tool would reduce the analysis time, the cost of analysis, and provide the courts with results more swiftly (Bueno et al. 2013; Janssen et al. 2015; Latzel et al. 2012a; Niewoehner et al. 2005; Zadora & Brożek-Mucha, 2003). Additionally, visualisation techniques could be a valuable tool to support GSR analysis by indicating where GSR is located on an item to assist with sampling accuracy and ensure that particulates are not overlooked (Atwater et al. 2006; Bailey, 2007; Bailey et al. 2006).

2.3.6.1 Visualisation of GSR

The difficulty of the collection of GSR is that these particulates are not visible to the naked eye, which makes them easy to be overlooked, as there is no indication of what areas to focus on during sampling. To allow for immediate sampling, different light sources have been investigated for the visualisation of GSR such as ultraviolet (UV) and visible light (Atwater et al. 2006; Bailey, 2007; Kersh et al. 2014)

When light is shone on forensic material, two types of interactions occur between light and matter: reflection and fluorescence (Horiba Scientific, 2006). The reflection of light occurs because the free electrons within the matter do not permanently absorb the light and instead release it almost immediately; fluorescence occurs when a given wavelength is absorbed by a molecule and is later released from the molecule at a longer wavelength than the one initially applied.

Studies have investigated these interactions on clothing for the visualisation of GSR. For instance, Kersh et al. (2014) visualised GSR using UV and visible light and determined that the optimum wavelength is 445 nm. Additionally, Atwater et al. (2006) used a Video Spectral Comparator 2000 (Foster and Freeman, Evesham) which uses UV and visible light for document examination. Thus, visualisation of GSR is possible to assist with sampling.

2.3.6.2 Detection and characterisation of GSR

The difficulty with determining a suitable alternative or screening tool for the SEM/EDX is that any analytical instrument would need to possess sufficient sensitivity to detect the GSR particulates (Schumacher & Barth, 2010). Thus, the focus has been on particle analysis because this technique analyses the elemental composition of the individual particulates (Bueno et al. 2013). Examples of particle analysis techniques are X-ray fluorescence (XRF), Raman spectroscopy, and IR spectroscopy (Bueno & Lednev, 2014; Janssen et al. 2015; López-López et al. 2013). These techniques have been considered because they are non-destructive, allowing for additional analysis. They also provide elemental composition data and allow for semi-quantitative analysis, whilst having a quick acquisition time. From all these techniques, the most promising results have been from XRF (Berendes et al. 2006; Kazimirov et al. 2006; Janssen et al. 2015).

XRF acts similarly to the EDX by using a source of excitation which causes electrons in the sample to undergo an electronic transition from the ground state, which is the state of lowest energy, to a higher energy or excited state. When a molecule in the excited state returns to its ground energy state, a portion of its excess energy is released (Siegel & Mirakovits, 2007; Wallace, 2008). Furthermore, XRF has multiple advantages, such as quick sampling time, a user-friendly interface and it is non-destructive (Kazimirov et al. 2006). Therefore, studies have preferred its use for the detection of GSR (Kazimirov et al. 2006; Berendes et al. 2006). The XRF technique is subject to some intrinsic limitations. First, it is very difficult to detect elements having atomic number <15 (phosphorus), owing to the low fluorescence yield and energy. This is not a concern for GSR characterisation as barium, antimony and lead all have an atomic number above 15. Second, the so-called matrix effect must be considered, i.e. the intensity of the emission of each element is determined both by its concentration and by the overall composition of the area under investigation. Lastly, the technique can detect only the various elements and not the compounds to which they belong.

The literature has demonstrated that XRF is able to detect GSR. For instance, Flynn et al. (1998) compared the use of X-ray micro fluorescence spectrometry to the SEM/EDX and concluded that even though GSR characterisation is possible, it is only possible for particulate sizes larger than 10 μm and only 'medium to 'high' concentrations. This is due to the instrument that was used, where the smallest beam collimator was 50 microns and limited power (maximum 50 W) of the X-ray tube. However, they do not establish the amount of GSR particulates they consider to be 'medium' or 'high' concentrations. Furthermore, a study by Kazimirov et al. (2006) successfully used XRF to investigate the composition of GSR and Berendes et al. (2006) used it to investigate the GSR pattern on fabric. Additionally, this study determined that a limitation to micro-XRF is that it has an acquisition time of up to 4 hours. Finally, the latest study by Janssen et al. (2015) demonstrated the use of m-XRF as a screening tool by analysing GSR from cartridge cases. They tested two different collection methods: the use of SEM stubs and gel-lifting. They found that GSR characterisation was possible and, even though both methods of sampling were successful, they noted that the SEM stubs can be too brittle for m-XRF analysis. The limitation to these studies is that they focus on the ability to detect, instead of empirically establishing the detection capabilities and limitations of the instrument. Thus, it remains unclear whether XRF should be implemented into practice as a screening tool or suitable alternative to the SEM/EDX.

Overall, it has been shown that a substantial amount of research has been undertaken to better understand the transfer, persistence and analysis of GSR. However, instead of providing insight into how GSR behaves, the literature demonstrates the complexity of analysing and interpreting GSR. One main limitation to these studies is that is currently not possible to obtain known samples of GSR. By obtaining such samples, it will be more likely to gain insight into the transfer as it would be possible to calculate the percentage of particulates transferred over between bystanders. Additionally, this will allow for an empirical decay curve to be established when analysing the persistence. Lastly, it will provide empirical data on the detection limit of any analytical technique. This raises questions on whether additional research can provide further insight into the behaviour of GSR, given this limitation.

2.4 The future of forensic science

So far, this chapter has advocated the need to perform empirical studies by looking into the role of experimental studies within the forensic process, and the complexity of gaining empirical insight into the behaviour of more complex forms of evidence such as GSR (National Council, 2009). However, before an evidence base can be implemented, it is important to also consider the current forensic science landscape in the UK and how experimental studies would fit into it. This is important because there are a variety of hindrances to consider that can reduce the impact of any additional research (Silverman, 2011; House of Commons, 2013; Forensic ScienceRegulator, 2016). For instance, forensic science in the UK is privatised (House of Commons, 2005). As a result, there are (1) more work pressure and time restraints placed on the practitioner, (2) collaboration hindrances as there is now a competitive market and thus (3) a lack of dissemination of research (House of Commons, 2011). This is further agitated by the fact that there are no admissibility criteria in the UK (Crown Prosecution Service, 2014). Thus, there is no demand for such research as interpretation based on experience is still being accepted in court. Given these circumstances, it is important to also review the current research landscape in forensic science to see if forming a research culture is possible. Thus, it is only by considering these different variables that research can progress to a point where an evidence base can be implemented to assist with interpretation.

2.4.1 The effect of privatising the forensic market

Since the UK is the only country that has a privatised forensic science service, there is a need to consider how experimental studies fit into this unique construct. The first concern when privatisation occurred, was that by entering a competitive market, there would be a 'work for profit' mentality: both the costs and time of analysis would be reduced to satisfy the customer and meet their demands (House of Commons, 2005). When the Forensic Science Service (FSS) was being shut down, it was argued that privatisation was the right course of action: the private forensic providers appeared to have faster turnaround times for products and services than public sector laboratories, which were severely backlogged (House of Commons, 2013). However, having quicker turnaround times means the practitioner must dedicate less time to a particular item, which can lead to evidence going uncollected. For instance, not all evidence could be collected on a sweater if a timeframe of its inspection is imposed on the expert (Lawless, 2010; Prospect House, 2011). With such time and work pressure on practitioners, it was unrealistic to expect practitioners to have the time to undertake additional research.

The second concern with privatising the forensic market is the occurrence of fragmentation of evidence, where items of evidence from the same case are sent to different providers (House of Commons, 2013). Even though the government reassured providers that fragmentation of casework is not general police practice, further investigation revealed that it was occurring more often than stated. However, there was no evidence to suggest that it was detrimental to cases (House of Commons, 2013; House of Commons, 2005). While this is true for straightforward cases, there may be specific situations where the context of the case and the information of the different types of evidence might be pivotal to accurately interpreting the overall results. If the evidence is fragmented, then this information will not be readily available. Additionally, there is no standardised approach to analysing and interpreting evidence; laboratories can have different methods and equipment, which could be problematic when putting the different types of evidence in context (Bencivenga, 2016; Grochau & Caten, 2012). Therefore, if fragmentation is occurring, this could affect research on the secondary level of experimentation as it is vital to have a clear overview of the evidence available and the state of that evidence. Additionally, by fragmenting evidence, such studies would require corroboration of these different companies as withholding any available information can affect the final results.

Due to these variations, the National Audit Office (NAO) reported there is a real danger of the standards of forensic science in the UK dropping (Burke, 2015). With this inconsistency of good practice across the UK, scientific evidence is more easily undermined in court and thrown out due to doubts about its credibility. Thus, quality standards such as ISO 17025 and ISO 17020 were introduced (Abdel-Fatah, 2010; Grochau & Caten, 2012). ISO 17025 is designed for analytical testing laboratories, which focus on measurement uncertainty and the proficiency at the identification and quantitation of a material (Bencivenga, 2016; Forensic Science Regulator, 2016). ISO 17020 is designed for the inspection processes based on professional judgement and tests an individual activity against established standards for that activity (Bencivenga, 2016). Unfortunately, these quality standards focus mainly on the maintenance of laboratory equipment or inspection processes, and do not realistically apply to a standardised strategy or approach to a case (House of Commons, 2013). For instance, these quality standards do not work out which items to examine, or assist with complex interpretation and presentation of the results. Therefore, the robustness of the evidence in court still needs to be addressed.

Further, to provide a more cohesive approach, the forensic science strategy report suggested a more national approach where tests are standardised - regardless of the forensic providers used - and the implementation of quality management (Home Office, 2016). However, this report was criticised by the Science and Technology committee for being vague, as no clear plan was outlined to reach such a goal (Science and Technology Committee, 2016). For instance, it stated a number of outstanding goals but very little on the best approach to raise forensic science to the standards it needs to be at. Whereas, in her annual report, the Forensic Science Regulator advocated that more research to produce data that can underpin the interpretation of trace evidence is needed (Forensic Science Regulator, 2016). If additional research was to be undertaken, then such research should follow forensic science protocol to increase its relevance for casework. However, if there are different approaches used in the different forensic laboratories, then there are still concerns with validity and reproducibility of such studies.

Reviewing these different concerns highlights that it is not just additional research that needs to be undertaken, but there is also a need for standardisation of practice and cohesion in the forensic science community. This is especially important given the complexity of the forensic science landscape in the UK.

2.4.2 Admissibility of forensic evidence

Given these hindrances, there are a range of variables that do need to be considered if additional research is to be undertaken. However, without being able to demonstrate reliability of evidence, the question of whether such evidence should be deemed admissible in court is raised. At this time, there is no set standard for the admissibility of evidence in the UK that needs to be met (Crown Prosecution Service, 2014). This means that now, not only are forensic practitioners unclear about whether additional research should be undertaken, the courts are also not demanding a higher standard of forensic interpretation as they continue to admit such evidence (Law Commission, 2011). This is further exacerbated as there is no admissibility criteria in the UK to guide judges on assessing the state of the evidence presented.

The Law Commission report discussed the lack of admissibility in the UK and proposed that the common law approach should be replaced with a new admissibility test: certain criteria need to be satisfied to demonstrate the reliability of forensic evidence before it can be admitted (Law Commission, 2011). Additionally, they suggested that there should be two separate sets of guidelines: one to determine the reliability of scientific evidence and one aimed at experience-based, non-scientific expertise. Unfortunately, the Science and Technology committee (2013) determined that a sufficiently strong case had not been presented to implement such a criteria due to financial concerns. Therefore, an admissibility criterion is currently not under development, let alone close to implementation in the British criminal justice system (CJS). This is a cause of concern as it indicates that the standards of forensic evidence provided are enough for the CJS, thus there is no incentive to perform experimental studies, which is noticeably needed to improve the current state of forensic science (Edwards, 2010; Law Commission, 2011).

Other countries have implemented standards of admissibility to assist the courts (Roberts et al. 2015). For instance, in the US, some states rely upon the *Daubert* standard which allows a judge to determine whether or not an item of evidence is admissible (Edmond & Mercer, 2004; Cheng & Yoon, 2005; Christensen et al, 2014). This is dependent on whether an expert's scientific testimony is based on a reasoning or methodology that is scientifically valid (Cheng & Yoon, 2005). This assessment is done by looking at five factors:

(1) whether the theory or technique in question can be and has been tested;

(2) whether it has been subjected to peer review and publication;

(3) the known or potential error rate;

(4) the existence and maintenance of standards controlling its operation;

(5) whether it has attracted widespread acceptance within a relevant scientific community.

Even though the UK courtrooms do not necessarily need to adopt the *Daubert* standard, there is a need for a set of criteria that forensic evidence should meet to be admissible in court (Law Commission, 2011). This would guarantee that the highest scientific standard is being met. It would also provide the necessary motivation for the sub disciplines of forensic science (such as pattern recognition or trace evidence) to: 1) establish a scientific method, improve their techniques and validate their methodology (Neufeld & Scheck, 2010; Cheng & Yoon, 2005); 2) perform further experimental studies to support forensic interpretations in court (Saks & Faigman, 2008; Quintieri & Weiss, 2005).

2.4.3 Key issues for Research & Development in forensic science

Currently, limited research is already being undertaken by forensic science providers and universities (Latzel et al. 2012; Peters et al. 2007; Edwards, 2010). However, the focus of this research is mainly on technological developments rather than addressing the interpretation of evidence (Silverman, 2011). Therefore, research might be addressing the lack of standardising forensic laboratories and meeting the requirements for the ISO-17025/ISO 17020 accreditation. However, such research does not address the concerns on the robustness, validity, and therefore the use of forensic interpretation in court.

This is exacerbated by the current state of the research landscape in forensic science. For instance, in 2011, the Silverman report concluded that "the whole research area is currently uncoordinated and not sufficiently integrated" (Silverman, 2011). Universities can support forensic science development but coordination is essential to minimise duplication and ensure the appropriate areas are explored. As a result, time is spent on repeating studies that others might have already tried, which wastes time and hinders advancement. Further, private forensic providers might perform research within their company but are often unwilling to share the research or results to external parties (Silverman, 2011). This lack of co-ordination is further exacerbated by the way research is disseminated. For instance, most research is undertaken at universities and are then published in academic journals. These journals are distributed within academic circles and are not read by practitioners to whom this information would be most valuable (Edwards, 2010). As such, the distribution of research is restricted and thus frequently fails to reach the required audience (Silverman, 2011). Moreover, for an evidence base to be effective, it requires rapid access to the best available evidence, suitably filtered to ensure efficient use (Djulbegovic, 2017). For instance, consider the number of articles published each year in each forensic science journal. There is limited research on the number of studies published per year. However, one study identified that the Journal of Forensic Science and the American Journal of Forensic Medicine and Pathology published combined 365 articles in 2005 (Sauvageau et al. 2009). This large influx of papers makes it more difficult for the practitioner to find the high quality and relevant research. Thus, it is important to identify a method to easily disseminate the required information.

To improve on the quality and dissemination of research, there is a need to have a dialogue between forensic academics, professionals and the other stakeholders of the courts, to make sure the right questions are addressed, and in a manner that makes the outputs applicable in the appropriate contexts (Saks & Faigman, 2008; Edwards, 2010; Silverman, 2011). When referring to the other stakeholders of the court, this signifies the judge, lawyers (prosecution and defence) and jurors. These key players are important to consider as it is the responsibility of the judge is to determine the admissibility of evidence; the responsibility of the lawyers is to evaluate and question the evidence presented in court; the responsibility of the jury is to evaluate the evidence presented to them to decide upon a verdict (Bolton-King, 2015). Throughout a trial, the only stakeholders who can demonstrate the weight of the findings and who can guide the jury through them are the lawyers and the forensic scientists. As such, it is important for the lawyers to have a better understanding of these weight of the findings and to communicate with the experts on the discrepancies in a particular case. This would also provide the forensic scientists with a better understanding of the areas of a forensic investigation that lawyers require further information on, to help ensure the appropriate areas are being researched.

However, as highlighted by the NAS report, lawyers and judges often have insufficient training and background in scientific methodology (National Research Council, 2009). As a result, judges and lawyers often fail to fully comprehend the approaches employed by different forensic science disciplines and the reliability of forensic evidence that is offered (Ledward, 2004). For instance, a study into the perspective of judges (n=400) in the US on scientific evidence and the Daubert standard of admissibility showed that 48% of the judges did not receive adequate training for handling forensic evidence (Gatowski et al. 2001). Additionally, 96% of judges had not received any instruction about scientific methods and principles. Yet, without this scientific training and knowledge, judges are expected to make decisions on admissibility and lawyers are expected to place the forensic evidence under sufficient scrutiny (Bolton-King, 2015).

Moreover, there has been more emphasis placed on the requirement for the lawyers to understand the scientific underpinning of forensic evidence, to assist with the concerns raised by the NAS report (Edmond & Roach, 2011; Risinger, 2009; Wheate, 2008). For instance, Wheate (2008) found that there was a high level of dissatisfaction from forensic scientists over the way that lawyers operate as they have an insufficient understanding of forensic results. This is due to inadequate pre-trial preparation and a failure to communicate. This limits the ability of lawyers to ask appropriate questions or to rebut any misleading information elicited by the opposing side. This lack of communication was further highlighted by the American Society of Crime Lab Directors (ASCLD) who argued that forensic practitioners need to engage and collaborate with non-experts, such as lawyers, to communicate the scientific underpinning of these individual fields (ASCLD, 2009). This would enable lawyers to ask for further clarification to ensure that they understand the strengths and limitations of the scientific findings (Howes et al. 2014; Cassella & McCartney, 2011).

This demonstrates that forensic science research and development has been hindered by the lack of communication between forensic practitioners, academics and the courts as these issues will only be addressed through collaboration and cooperation. The Silverman report reviewed the current research landscape in forensic science. It concluded that "the whole research area is currently uncoordinated and not sufficiently integrated. Universities can support forensic science development but coordination is essential to minimise duplication and ensure the appropriate areas are explored" (Silverman, 2011). Furthermore, when the NAS report was released, practitioners argued that their experience was sufficient to accurately interpret forensic evidence as there are only certain skills and judgements that can be made through gaining experience (Koehler & Meixner, 2016). Additionally, due to their heavy casework load, they do not have the time to undertake further research. This means that the responsibility falls onto forensic academics. However, practitioners argued that academics do not have the practical experience to provide forensically realistic research (Koehler & Meixner, 2016). Therefore, the research outcomes will not be applicable to casework as researchers try to account for every variable whereas forensic science always has to deal with certain unknown factors. This demonstrates the need for an increase in communication between forensic researchers, practitioners and lawyers. The right research will only be done where there is dialogue between academics, professionals and the courts, to make sure the right questions are addressed, and in a manner that makes the outputs applicable in the appropriate contexts (Saks & Faigman, 2008; Edwards, 2010; Silverman, 2011).

Research into forensic science communication has emphasises that clear communication is essential to the effectiveness and perceived trustworthiness of the criminal justice system (Howes, 2015). However, such communication is complex due to the variety of audiences that forensic scientists communicate with. For instance, the primary audience that forensic scientists communicate their findings with are not other scientists, but a range of non-scientists including police investigators, lawyers, judges, and jurors. These findings are used to assist with police investigations, out-of-court settlements, and trials. Thus, ensuring all parties understand forensic findings is vital to avoid miscarriages of justice.

Further, the NAS report identified that further dialogue is require before progress in forensic science is possible. However, this requires both legal professionals and forensic scientists to understand the basic principles and language of both science and law (Cassella & McCartney, 2011). This will ensure that all the stakeholders involved on a case have a clear understanding of the weight of findings. This is especially important as research has shown that the legal community and jury often overvalue forensic findings (Cashman & Henning, 2012;

Ligertwood & Edmond, 2012; Wheate, 2008). For instance, Cashman et al. reviewed the literature on the scientific understanding of lawyers on forensic DNA results (Cashman & Henning, 2012). They highlighted that improving communication between forensic scientists and lawyers by having more meetings will provide the opportunity to seek clarification on findings and ensure that the barriers between lawyers and forensic scientists are overcome. To determine a way to develop the communication between lawyers and forensic scientists, McCartney and Cassella (2013) held a workshop to academics and practitioners from scientific and legal backgrounds. From this workshop, they recommended improved communication of forensic evidence and its limitations in and out of court. This would be improved by looking into the formatting of written reports and orally by improving communication between the courts and forensic scientists (Edmond et al. 2016; Howes et al. 2014; McCartney & Cassella, 2013). By improving such communication, it will assist those who are presented with scientific evidence to understand the evidence and allow them to assess findings by identifying common errors or misunderstandings and gain insight into the reliability of a technique (McCartney & Cassella, 2013). That is, provide lawyers with a rudimentary understanding of the scientific method and basic statistics.

Lastly, increasing communication between these parties needs to cross over internationally: even though laws and admissibility criteria differ, it is important to determine a standardised approach for different forensic procedures by exchanging information, in order to provide a worldwide evidence base in the forensic field (Law Commission, 2011; Silverman, 2011). This is important, as undertaking research to establish the scientific foundation in forensic science is a time-consuming task, and therefore by collaborating on this endeavour, it would provide results sooner rather than later (Silverman, 2011; Saks & Faigman, 2008).

Overall, reviewing the current R&D in forensic science highlights that there is a need to improve on communication and collaboration if the research landscape is going to become more cohesive. Additionally, even though the current research being undertaken is valuable, there is a need to widen the research scope and undertake experimental studies that address the lack of scientific underpinning in forensic science and implement an evidence base in forensic science.

2.5 Aim and research questions

Overall, the arguments put forward in this review of the literature are demonstrating that there is a need to investigate the use of experimental studies on more complex forms of evidence. When the NAS report was released, it highlighted concerns of the continued use of forensic science in court (National Research Council, 2009). Thus, to demonstrate reliability and validity of results, there is a need to follow an evidence-based approach in forensic science. This was demonstrated by reviewing the complexity of interpreting GSR due to its ability to transfer and persist, but also the way it generates and distributes (Brozek-Mucha, 2014; Charles & Geusens, 2012; James French et al. 2014). Further, to implement an evidence base and assure its efficacy, there is a need to understand the current forensic science landscape and the way experimental studies would fit into it. This highlighted that for additional research to have an impact, there is a need for improved communication and collaboration between forensic scientists (Howes, 2015; Silverman, 2011). Thus, the aim of this thesis is to explore the complexity of implementing an evidence base in forensic science.

To address this aim, this thesis will investigate the following questions:

1) What is the impact that additional research can have on forensic interpretation and can it account for complex forms of evidence such as GSR?
2) How much consideration has been given by forensic scientists and criminal lawyers on research evidence as a foundation on which to make forensic decisions?
3) In the light of the findings of questions 1 and 2, what are the key recommendations to the forensic science community to improve communication between forensic scientists and criminal lawyers on casework and on research?

Chapter 3: Experimental studies on the distribution, persistence and analysis of GSR

3.1 Introduction

It has been demonstrated that there is a need to establish the scientific bases for the forensic disciplines to enable forensic analyses to act as reliable and admissible evidence (Gherghel et al. 2016; Morgan et al. 2009; McElhone et al. 2016). One approach that can offer insight into the dynamics of forensic evidence and lay an empirical foundation for the collection, analysis, interpretation and presentation of such evidence is casework informed experimental studies. Such an approach promotes the importance of generating reproducible data to establish the variability of the transfer, persistence and preservation of trace materials. In addition, such an evidence base offers a means of informing the interpretation of trace materials found in specific contexts (Saks & Faigman, 2008; Budowle et al. 2009; Morgan et al. 2008; Morgan et al. 2009).

Even though establishing such an evidence base has provided better insight into the dynamic of different types of evidence, it has also highlighted the difficulty of empirically establishing the behaviour of certain types of evidence. For instance, research into the transfer and persistence of GSR has demonstrated the variability in its behaviour, and thus the difficulty of interpreting the presence of GSR on a particular person or item (French et al. 2012; Lindsay et al. 2011; Charles & Geusens, 2012). For instance, research has been undertaken on the spatial distribution of GSR to determine the way it will disperse after a firearm is discharged. One study by Fojtasek et al. (2003) found that when mapping the distribution of GSR on smooth surfaces, while GSR would travel in all directions around the shooter, the maximum quantity was found at 45 degrees to their right. This trend occurred whether in an indoor and outdoor environment, where the magnitude of the GSR was reduced when outdoors. However, studies to date have shown that this distribution is dependent on the location, the climatic conditions and the type of weapon used (Ditrich, 2012; Gerard et al. 2011; Fojtášek et al. 2003).

Other studies have focussed on the possibility of distinguishing between the bystanders and shooter using variations in the distribution patterns (French & Morgan, 2015; Lindsay et al. 2011). For instance, French et al. (2015) demonstrated that when bystanders are 1m behind a shooter, it is difficult to differentiate between shooters and bystanders based on only the particulate count of GSR on the hands. Even though most studies of this nature have only investigated the hands of the shooter and bystanders, the interpretation of GSR is complicated because GSR has shown to transfer or shed easily (French et al. 2014; French & Morgan, 2015; Rosenberg & Dockery, 2008). For instance, French and Morgan (2015) demonstrated that a high number of GSR particles (21-36) were found on a bystander standing behind a shooter. Additionally, they showed the potential of GSR to undergo tertiary transfers and as a result implicating an unconnected individual to the crime. Therefore, an improved understanding into the mechanisms of GSR transfer on clothing needs to be considered when interpreting the meaning behind finding a GSR particulate on a person. As such, gaining better insight into the transfer of GSR may provide a better idea of the relation of the bystander to the shooter based on the areas on the clothing where GSR is retained. For instance, it might be possible to see a pattern where a witness facing the shooter on their left will have more GSR on the right side of the clothing compared to the left. Further, the witness to the right would have the mirror image of the witness standing to the left of the shooter.

Further, the persistence of GSR on clothing needs to be considered when interpreting the presence of a particulate at the activity level. For instance, it is common that sampling does not occur until a suspect is apprehended and taken to the police station (Charles et al. 2013). At this point, it is possible that all the particulates have shed from the clothing. Thus, establishing the persistence of GSR on clothing under different scenarios will provide insight into whether it is still worth sampling (Dalby et al. 2010). Limited research has been undertaken on the persistence of GSR on clothing. Nevertheless, the literature has shown that GSR on clothing can persist for days or even weeks after the initial transfer (Mastruko, 2003; Cwiklik and Taupin, 2011). For instance, Dalby et al. (2010) demonstrated a case where GSR was recovered from the clothing of a badly decomposed man after the body was outside for 2 months. However, this timeframe fluctuates depending on other variables such as physical activity, material type, with the smoothness of the fabric being particularly pertinent (Charles et al. 2013). Additionally, research has also shown that particulates tend to reincorporate from higher to lower garments indicating that particles might remain on the lower garment for longer (Morgan et al. 2010). Therefore, these different variables need to be considered when performing research into the persistence of GSR. Regardless, since the extent to which these variables can affect GSR retention is still unclear and has not yet been empirically established. Therefore, most investigating departments in the United Kingdom (UK) have a general procedure where sampling with stubs is usually only performed within 24 hours after the incident (Shaw, 2013).

To support GSR interpretation, there is also a need to improve upon the analysis of GSR (Atwater et al. 2006; Kersh et al. 2014; Romolo & Margot, 2001). Currently, the technique used to analyse GSR samples is SEM/EDX (Wallace, 2008). However, SEM/EDX takes a long time to carry out the analysis causing delays in the investigation (Berendes et al. 2006; Bueno & Lednev, 2014; Janssen et al. 2015). To improve upon sampling accuracy, there are now a range of forensic light sources on the market such as the light sources by Advanced NDT ltd, Advanced Forensics, and Foster and Freeman to visualise GSR. These light sources are portable to use in situ, require no added chemicals, are non-destructive and easy to hold at different distances and angles from the surface being visualised to get the right exposure. Additionally, these light sources provide illumination in wavebands across the ultra-violet (UV) to infrared (IR) range to visualise different evidence types. To demonstrate the use of such light sources for GSR visualisation, Kersh et al. (2014) investigated the use of alternate light sources (ALS) to visualise GSR on dark coloured (black, navy blue and blue) fabrics. They used a Forensic Mini-Crimescope MCS 400 by Spex Forensics which provides light sources between 300-630 nm. They found that the optimum setting for GSR visualisation on dark clothing was between 445 and 495 nm, regardless of firearm type. However, in these studies, only dark fabric was considered and it remains unclear how these light sources would interact with GSR on white fabric. Black fabric is usually preferred for testing as it usually provides a greater contrast between a particulate and the background fabric whereas white fabric will fluoresce as well. Other light sources such as Advanced NDT ltd and Advanced Forensics do not advertise the use of these light sources for the visualisation of GSR. However, the Crime-lites 82S, developed and provided by Foster and Freeman, is advertised to visualise GSR with the blue and blue/green light sources (Evesham, UK).

To improve upon the analysis of GSR, the published literature has looked into XRF for a screening tool to characterise GSR in situ (Flynn et al. 1998; Schumacher & Barth, 2010; Shackley, 2011). Preliminary studies into the use of XRF for GSR characterisation has shown its ability to characterise GSR (Berendes et al. 2006; Latzel et al. 2012b). For example, Flynn et al. (1998) compared the use of the X-ray micro fluorescence spectrometry to the SEM/EDX, Berendes et al. (2006) looked into the use of the m-XRF to characterise GSR on clothes. Janssen et al. (2015) investigated the use of the m-XRF to determine the elemental composition of GSR from cartridge cases (more detail in chapter 2 section 2.3.6.2). However, these studies only highlight that GSR detection is possible, and provide little information on the detection limits to understand the accuracy of the instrument.

When looking at the transfer, persistence, and analysis of GSR evidence, the published literature has already undertaken a wide-range of research. However, this research has merely highlighted the complexity of GSR interpretation. Thus, there is still a need to undertake further experimental studies to better establish the conditions and timeframes in which this form of evidence transfers and persists. Such an evidence base will provide a means to aid the interpretation of the presence of GSR evidence on a particular item of clothing (Gherghel et al. 2016; McElhone et al. 2016). Additionally, there is a need to improve upon the analysis of GSR in situ to assist with sampling accuracy and analysis. This chapter therefore aims to investigate the impact that additional research can have on forensic interpretation and whether it can it account for the more complex forms of evidence.

To address this aim, this chapter performed a study to investigate the spatial distribution of GSR on bystanders near the shooter (experiment 1a). Additionally, a quantitative study was undertaken to investigate the amount of GSR a bystander standing behind a shooter and a bystander standing behind to the right of the shooter will retain (experiment 1b). The persistence of GSR particles on the bystanders was also examined by investigating the timeframe within which GSR is still detectable on bystanders (experiment 2). Lastly, the potential use for p-XRF as a screening tool for GSR analysis in situ was investigated (experiment 3). The following hypotheses were presented for each study:

<u>For experiment 1a:</u>

H1: The spatial distribution of GSR will demonstrate a clear pattern for accurate crime reconstruction when a firearm is discharged under the same experimental conditions.

H2: A witness standing behind the shooter to the left will have more GSR on the right side of their body and the witness standing behind the shooter to the right will have more GSR on the left side of their body resulting in the GSR distribution having a mirror image when comparing the two witnesses. Additionally, a witness standing behind a shooter will have less GSR on the clothing due to the shielding of the shooter.

H3: The distribution of GSR will vary depending on the external weather when performed under the same experimental conditions i.e. a day in January and a day in June.

<u>For experiment 1b:</u>

H4: The number of GSR particulates on the clothing of a bystander will be similar when repeating the same experimental layout consecutively after each other under the same experimental conditions.

H5: The number of GSR particulates on the clothing of a bystander will vary depending on the external weather when performed under the same experimental conditions i.e. a day in January, a day in April and a day in July.

H6: When comparing a bystander standing behind a shooter to a bystander standing behind to the right of a shooter, the bystanders will retain similar amounts of GSR particulates when repeated consecutively after each other under the same experimental conditions

H7: When comparing, a bystander standing behind a shooter to a bystander standing behind to the right of a shooter, the distribution of GSR on the bystanders will vary depending on the external weather when performed under the same experimental conditions i.e. a day in January, a day in April and a day in July.

<u>For experiment 2:</u>
H8: GSR will persist on clothing up to 12 hours after a shooting on bystanders when resuming their daily activities
H9: Overall, bystanders will exhibit similar GSR retention times regardless of their different daily activities.

<u>For experiment 3:</u>
H10: The p-XRF will detect GSR on white fabric when analysing the areas where the Crime-Lite has visualised GSR, regardless of firearm type.

3.2 Experiment 1: The spatial distribution of GSR on bystanders

3.2.1 <u>Method</u>

For experiment 1a, three participants stood around the shooter at a distance of 1m in each direction (Figure 6) to simulate the case scenario of a shooter firing while standing in a group. The shooter then discharged the firearm 5 consecutive times to deposit GSR onto the clothing of the participants. Each participant wore denim jeans (60% cotton, 30% polyester, and 10% elastane) and a hooded sweatshirt (70% cotton, 30% polyester) to represent commonly worn garments amongst the general public. Between each run, the witnesses changed clothing by handing over each individual item which was then placed in individual brown paper bags as is standard GSR collection procedure (Taupin, 2011). The witnesses would then change into new pair of clothing at the range in between firings, as there were no changing facilities available. They changed around the corner from the shootings to decrease the possibility of contamination. However, there were no changing or cleaning facilities to wash their hands or protect the clothing from the environment. Experiment 1a was performed twice in June and three times in January. The experiment was repeated to assess the variability in the detection of GSR and was performed on two different days to account for different weather conditions.

For experiment 1b, two participants stood around a shooter where one participant stood behind the shooter (Witness 2, Figure 6), and another participant stood behind to the right of the shooter (Witness 3, Figure 6) at a distance of 1m to simulate the case scenario of a shooter firing whilst bystanders are standing around the shooter (French & Morgan, 2015).

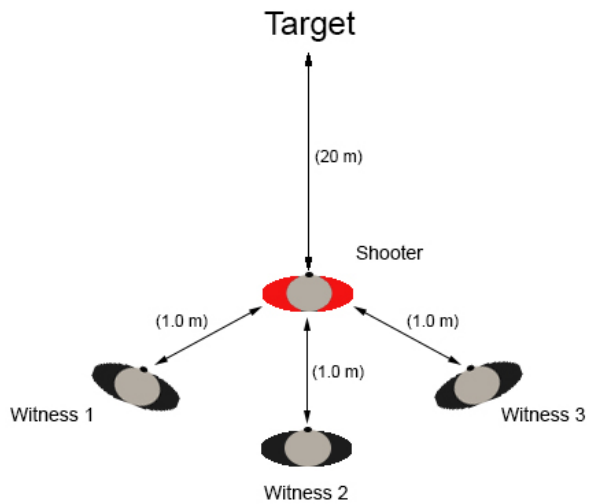


Figure 6. The positioning of participants in each of the experiments

Experiment 1a was designed to establish the extent to which GSR can be transferred to bystanders. The garments were divided into multiple sections for sampling purposes (Figure 7). Samples were taken from the front and back of the right (RA) and left arm (LA), the front (F), the hood (H), back (B) of the hooded sweatshirt, and from the front of the trousers (T). This experiment was performed five times where the different areas of the clothing of each of the three bystanders were sampled to generate in total 90 samples.

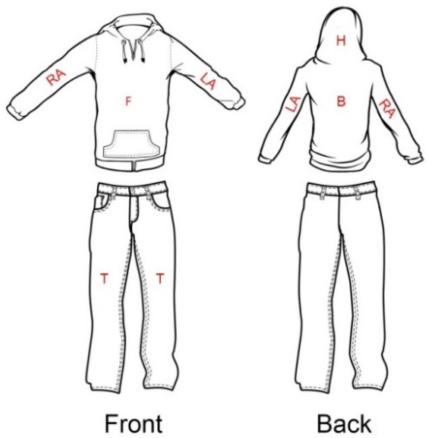


Figure 7. The areas that were sampled for experiment 1a

Experiment 1b was designed to investigate the amount of GSR a bystander standing behind a shooter will retain. This experiment was performed three times on each day and was performed on three different days: a day in January, in April and in July to account for the different weather conditions. The garments were divided into multiple sections for sampling purposes (Figure 8). Samples were taken from the front and back of the right (RA) and left arm (LA), the front of the hooded sweatshirt (LF, MF, and RF); and from the front of the trousers (LT, MT, and RT). This experiment was performed on two bystanders where one was standing behind a shooter and the other was standing behind to the right of the shooter nine times to generate in total 144 samples.

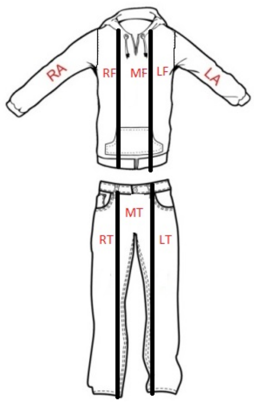


Figure 8. The areas that were sampled in Experiment 1b

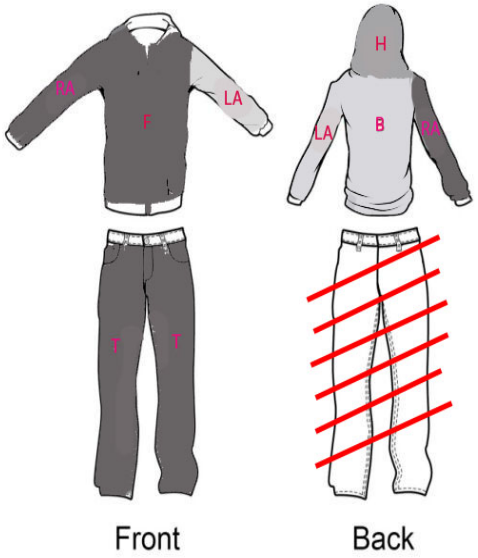
For each experiment, samples were taken via tape-lifting using ½ inch aluminium stubs coated with adhesive black carbon discs, where one sample was the equivalent of 15 dabs utilising a single stub. It was determined that 15 dabs could be taken before the stubs lose their stickiness by using a test stub on one of the hooded sweatshirt prior to GSR deposition. All the samples obtained from experiment 1a were then analysed by SEM/EDX (scanning electron microscope/ energy dispersive X-ray analysis) to determine the presence or absence of GSR. The samples obtained from experiment 1b were analysed on a JEOL JSM 6610V variable pressure scanning electron microscope with Oxford Max50 X-ray EDS (energy dispersive x-ray spectroscopy) system with INCA GSR software. The particulates were then characterised using the 2010 ASTM (American Society for Testing and Materials) standard criteria (Lentini, 1995).

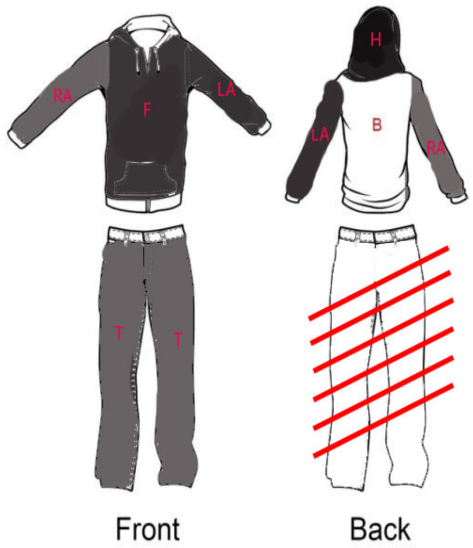
For the statistical analyses, a Kruskal-Wallis H test was used to test if there were significant differences in the amount of GSR detected across the different clothing areas, the different days, the different runs, and the individual runs on the different days. The Kruskal-Wallis test computes if there are significant differences between the values observed in each group (e.g. clothing area) when all those values are listed and ranked. This non-parametric test (and the ranking procedure) is used due to likely violations of the data being normally distributed which is required for the more-powerful parametric analysis of variance. When significant differences between ranks are detected, the Dunn's post-hoc test is used to pairwise compare the differences between each group to identify specifically where the significance lies. Also, the p-values from the Dunn's test are adjusted for multiplicity using the Bonferroni correction procedure to prevent falsely detecting significant effects when they are not present.

When comparing the amounts of GSR detected between the two witnesses, a Mann-Whitney U test were computed. This is because there are only two groups (witness 2 and 3) being compared, whereas the Kruskal-Wallis test allows multiple groups to be compared.

3.2.2 Results

The results show that there is no measured pattern in the way GSR distributes on the clothing of bystanders (Figures 9, 10 and 11) regardless of the day. For instance, GSR was detected on the right arm of witnesses 1 and 2 for 3/5 runs. Whereas, GSR was detected on the right arm of witness 3 for only 1/5 runs and was detected on the left arm of witness 1 for 1/5 runs, on witness 2 for 4/5 runs and witness 3 for 2/5 runs





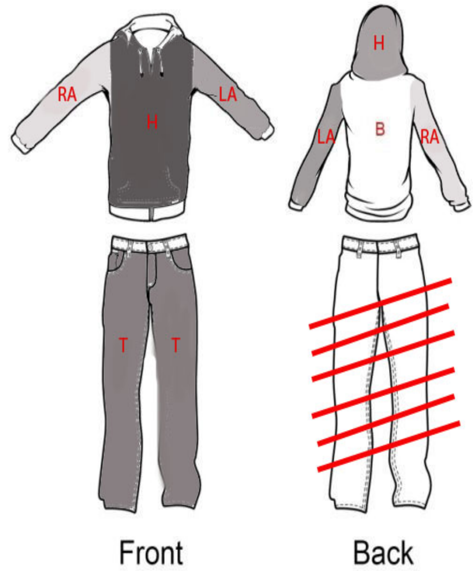


Figure 9. A summary of the spatial distribution on witness 1 from all 5 runs

Figure 10. A summary of the spatial distribution on witness 2 from all 5 runs

Figure 11. A summary of the spatial distribution on witness 3 from all 5 runs

This experiment was performed on two different days where runs 1 and 2 were performed in June and runs 3, 4 and 5 were performed in January. On visual observation, there does not appear to be any difference between the two days as there is no obvious pattern in the spatial distribution. This lack of pattern could be because even though the temperatures were different on both days (June was 15° C whereas in January it was 7° C), they were both windy. Therefore, it is possible that the climatic conditions affected the distribution pattern.

3.2.2.1 Participant standing behind the shooter (Witness 2)

Experiment 1b was undertaken to quantitatively demonstrate the variability of the amount of GSR retained on bystanders standing around a shooter (Table 2). It was also thought that the different days would yield different results due to the variation in weather, for example, the wind speed and direction. As such, this experiment was performed on three different days where three runs were performed on a day in January, a day in April, and a day in July.

When looking at the different particulate counts, there was no obvious visual pattern regarding the amount of GSR retained on the different areas of the clothing of witness 2 for crime reconstruction purposes (Table 2).

Table 2. A summary of the results of witness 2 for experiment 1b showing the amount of GSR particulates (characteristic and consistent only) found on the different areas of the body for three runs on a day in January, April and July. The different areas are LF (left front), MF (middle front), RF (right front), LT (left trousers), MT (middle trousers), RT (right trousers), LA (left arm), and RA (right arm)

		January			**April**			**July**		
Run		1	2	3	1	2	3	1	2	3
Sample Locations	LF	2	0	5	0	0	0	0	0	0
	MF	3	2	9	5	3	53	5	3	61
	RF	2	2	20	5	2	4	5	2	11
	LT	3	3	2	3	1	0	3	1	4
	MT	5	2	2	5	5	16	5	5	26
	RT	1	4	4	6	3	9	6	3	18
	LA	1	9	11	2	5	2	2	5	2
	RA	1	1	5	6	5	2	6	5	2

However, a Kruskal-Wallis test showed there was a statistically significant difference in the particulate counts between the different body parts, $\chi^2(7) = 23.34$, $p<0.01$ (see also Table 3 for the mean ranks where, for example, LF has a much smaller mean rank and so less GSR is found compared to MF). According to the Dunn's test, the only significant pairwise differences are where the left front has significantly less GSR than the middle front ($p<0.01$), right front ($p<0.05$), the middle trousers ($p<0.01$) and the right trousers ($p<0.01$).

Table 3. The Mean Ranks of the Kruskal-Wallis test demonstrating which body part has the higher mean rank of GSR

Body part	Mean rank
left front (LF)	11.50
Middle front (MF)	47.78
Right Front (RF)	40.33
Left Trouser (LT)	25.11
Middle Trouser (MT)	47.89
Right trouser (RT)	45.61
Left arm (LA)	36.44
Right Arm (RA)	37.33

When looking at the individual runs on each day, a Kruskal-Wallis test demonstrated that there was no significant difference between the three different days and the GSR count. When looking at the individual days, a Kruskal-Wallis test showed that there was a significant difference between the three different runs in January and the GSR count χ^2 (2) =6.60, $p<0.05$. The Dunn's test (adjusted for multiplicity using the Bonferroni correction: see also Method) showed that run 1 has significantly less GSR than run 3 ($p < 0.05$). Additionally, a Kruskal-Wallis test demonstrated that there was no significant difference between the three different runs performed in April and in July.

When further investigating the distribution of the GSR counts, a Kruskal-Wallis test demonstrated that there was no significant difference between the three different runs and the particulate count.

3.2.2.2 Participant standing behind to the right of the shooter (Witness 3)

When looking at the different particulate counts, there was no obvious visual pattern regarding the amount of GSR retained on the different areas of the clothing of witness 3 for crime reconstruction purposes (Table 4).

Table 4. A summary of the results of witness 3 for experiment 1b showing the amount of GSR particulates (characteristic and consistent only) found on the different areas of the body for three runs on a day in January, April and July. The different areas are LF (left front), MF (middle front), RF (right front), LT (left trousers), MT (middle trousers), RT (right trousers), LA (left arm), and RA (right arm)

		January			April			July		
Run		1	2	3	1	2	3	1	2	3
Sample	LF	3	6	13	4	8	6	3	0	0
	MF	7	11	16	11	9	8	10	4	6

	RF	4	3	12	1	4	15	8	4	6
	LT	3	19	29	23	7	1	7	2	4
	MT	0	8	8	9	12	13	17	26	0
	RT	6	0	22	5	4	2	67	31	4
	LA	9	11	0	1	4	5	8	0	0
	RA	6	26	13	2	7	17	3	4	3

When looking at the different body parts (Table 4), a Kruskal-Wallis test showed that there was no statistically significant difference in the particulate counts between the different body parts. Given the lack of any statistical difference, no post-hoc Dunn's test was computed.

When comparing the three different days to each other, there was no obvious visual pattern. Further, a Kruskal-Wallis test demonstrated that there was no significant difference between the three different days and the particulate count. When looking at the three runs in January, runs 2 and 3 appear to have a higher particulate count than run 1. Further, a Kruskal-Wallis tests showed that there was a significant difference between the three different runs in January and the particulate count χ^2 (2) =6.60, p <0.05. The Dunn's test showed that run 1 has significantly less GSR than run 3 (p<0.05). When looking at the three runs in April and in July, the middle trousers (MT) appear to retain more than the other areas of the body which stay reasonably consistent. Additionally, a Kruskal-Wallis test demonstrated that there was no significant differences between the three different runs performed in April and in July.

3.2.2.3 The comparison of GSR retention on Witness 2 to Witness 3

When comparing the overall GSR count between witness 2 to witness 3, a Mann-Whitney test showed that there is a statistically significant difference between the two witnesses (Z=-3.22, p <0.01). That is, there was more GSR detected on witness 3 than on witness 2.

When comparing the different body parts between witness 2 to witness 3, Mann-Whitney tests were computed to compare the amounts of GSR detected on the different body parts between the two witnesses. The results showed there was significantly more GSR detected on witness 3 than witness 2 in the left front (LF) (Z=-2.50, p<0.05) and left trousers (LT) (Z=-2.19, p < 0.05). In the other body parts, there was no significant difference. That said, in all body parts except LA, there was more GSR (but not significantly) on witness 3 than witness 2.

Mann-Whitney tests were also computed to compare the amounts of GSR detected on the different days between the two witnesses. The results showed there was significantly more

GSR detected on witness 3 than witness 2 in January (Z=-2.96, p<0.01) and in April (Z=-2.12, p<0.05). In July, there was no significant difference between the two witnesses. That said, there was more GSR (but not significantly) on witness 3 than witness 2 in July. Further, Mann-Whitney tests were computed to compare the amounts of GSR detected on the different runs between the two witnesses. The results showed there was significantly more GSR detected on witness 3 than witness 2 on run 1 (Z=-2.52, p<0.05) and run 2 (Z=-2.99, p<0.01). In the other body parts, there was no significant difference between the witnesses on run 3. On visual inspection, there was still more GSR on witness 3 than witness 2 in run 3.

3.3 Experiment 2: The persistence of GSR on clothing

3.3.1 Method

Experiment 2 was designed to establish the persistence of GSR on the garments of bystanders over a duration of time after the shooting. The transfer of GSR onto the clothing of the three bystanders was accomplished by following the procedure outlined in experiment 1 (Figure 6). After the firings, a control sample was taken from the arm of witness 2 to confirm that the clothing had captured GSR during the shooting. After the initial transfer, the witnesses continued wearing the clothing for a 12-hour period whilst resuming their regular routines. After this timeframe, the items of clothing were packaged in individual paper bags.

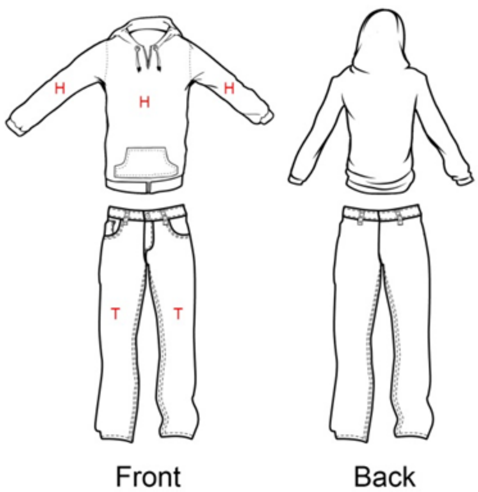


Figure 12. The areas of clothing sampled for experiments 2

During this period, two samples were taken from each witness, one from the hooded sweatshirt and one from the jeans, after 2, 4, 6 and 12 hours after the initial transfer (Figure 12). Even though the current standard procedure in the UK is to sample clothing via tape-lifting for GSR up to 24 hours after a shooting, this time frame was selected as it is the general timeframe of a workday (including commute). This experiment was performed twice generating 24 samples by having two samples taken at each interval on all three bystanders. All the samples obtained from experiment 2 were then analysed by SEM/EDX (scanning electron microscope/ energy dispersive X-ray analysis) to determine the presence or absence of GSR.

3.3.2 Results

The results derived from experiment 2 (runs 1 and 2) indicate that GSR particulates can persist on clothing for up to 12 hours after the initial transfer event when resuming their daily activities, as shown by the clothing of witness 2 (hooded sweatshirt and jeans, Table 5). However, it was observed that the clothing worn by each witness retained GSR for different durations of time where each witness had GSR that was recoverable from their clothing present for a minimum of 4 hours.

Table 5. A summary of the results of experiment 3 where 'yes' meant that at least one GSR particle whether 'characteristic with' and 'consistent of GSR' were detected. 'No' meant that GSR was undetected

Time		2h	4h	6h	12h
Witness 1	Hooded sweatshirt	Yes	No	No	No
	Jeans	Yes	Yes	Yes	No
Witness 2	Hooded sweatshirt	Yes	Yes	Yes	Yes
	Jeans	Yes	Yes	Yes	Yes
Witness 3	Hooded sweatshirt	Yes	Yes	No	No
	Jeans	Yes	Yes	Yes	No

Overall, the findings from this study suggest that after a criminal act, that whilst GSR particles may shed at different rates, broadly the particles persist for at least 4 hours with some items of clothing still having GSR particulates present after 12 hours.

3.4 Experiment 3: the use of the Crime-Lite 82S and the p-XRF for in situ GSR sampling and analysis

3.4.1 Method

Experiment 3 was designed to establish whether the p-XRF would detect GSR on white fabric when combined with the Crime-Lite 82s to identify the location of GSR on the fabric, regardless of firearm type.

3.4.1.1 Equipment used

The following light sources were used: white (400-700nm), UV (350-380 nm), violet (395-425 nm), blue (420-470 nm), blue-green (445-510 nm), and green (480-560 nm) (Figure 13).

Figure 13. An example of the crime-Lite 82S by Foster and Freeman

All samples were photographed using a Canon DSLR 750 D 24 MPixel. CMOS (Complementary metal–oxide–semiconductor) sensor with an 18-55 mm lens. The camera was programmed to manual exposure, a shutter speed of 1/100 s, aperture f/11. These settings were chosen as they provided the clearest images. The camera was set to ISO 200 and a resolution of 18 MP.

The p-XRF measurements were performed using a handheld portable InnovX XRF Olympus Delta Premium (Figure 14). This system is equipped with a 40kV tube, and used 200 µA current (max) and a spot size average 9 mm. There are several modes on the p-XRF to specify the elements of choice. In this experiment, the 'soil' mode was chosen as this mode contains the three elements of interest. Prior to use, a calibration check was required to ensure that the instrument would accurately detect barium, antimony and lead. Since characteristic x-rays are the main factor in making an XRF measurement, it is essential to be able to accurately measure their energies; this can only be done after a calibration is performed (Potts & West, 2008). For the p-XRF, calibration is completed by placing the instrument into the holder and instigating an automated calibration check which takes 1-2 minutes. Calibration is accomplished as there is a steel of known composition on the base unit which is used to look at the peaks and concentration of the standard.

Figure 14. The experimental setup of the p-XRF experiments

Overall, 9 white, cotton swatches were analysed. From these 9 swatches, 4 swatches were seeded with GSR by wiping it around an SA80 assault rifle and 5 swatches were seeded with GSR by wiping it around a Glock 17 semi-automatic pistol (see Table 6). The swatches that were seeded by the Glock 17 were wiped around the gun after 50 rounds. The swatches that were seeded by the SA80 were wiped around the gun after 60, 65, 70, and 110 rounds. Different rounds were used due to access to sampling as these swatches were taken in correlation with a different set of experiments. Ideally, the swatches would have been wrapped around a firearm after discharged the same number of rounds. However, it has been shown that the number of rounds discharged does not affect this experiment (Schwoeble & Exline, 2000).

Table 6. A summary of the swatches of fabric analysed

Swatch	Type of Firearm	Rounds
1	SA80	65
2	Glock 17	50
3	Glock 17	50
4	Glock 17	50
5	SA80	70
6	SA80	110
7	Glock 17	50
8	SA80	60
9	Glock 17	50

3.4.1.2. Method

First, swatches 1 and 2 were chosen (Table 6); one seeded by the SA80 and the other by the Glock 17. Then, each light source was placed over the swatches to confirm that the blue-green light source was the most efficient at visualising GSR. Before using the p-XRF for GSR characterisation, a background sample of the work bench and a fresh, blank fabric swatch was taken for comparison purposes. After which, the 9 swatches of fabric seeded with GSR were analysed by placing them on the lab benchtop and shining the blue and blue-green light sources over each swatch to visualise where on the item GSR was located. These areas were identified and encircled with a pen. The p-XRF was then held above the encircled areas to characterise the visualised particulates. This was done 2 to 3 times depending on the ease of GSR detection on the fabric because it was often seen when analysing 2 different areas that GSR was detected, whereas when neither times GSR was detected, a third attempt was made to act as confirmation.

3.4.2 <u>Results</u>

The results derived from experiment 3 indicate that the p-XRF combined with the Crime-Lite 82S light sources can visualise and characterise GSR.

3.4.2.1 Crime-Lite sources

All the light sources were tested on the two swatches of fabric, one seeded with GSR from a Glock 17 (Swatch 2, Figure 15) and the other seeded with GSR from an SA80 (Swatch 1, Figure 16). This was to confirm that the blue-green light source is the most efficient at visualising GSR as it is advertised by Foster & Freeman. It should be noted that when looking at Figures 10 and 11, visualisation was easier to see through the camera whilst taking the photograph than on the photograph itself.

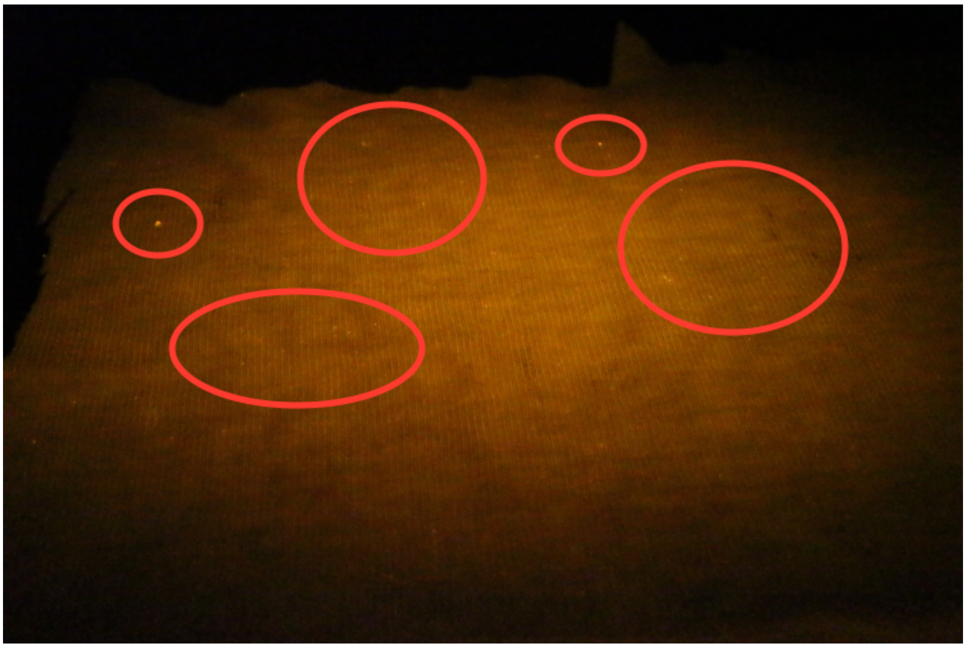


Figure 15. A swatch of fabric seeded with GSR from a Glock 17 visualised under blue-green light, the bright spots

Figure 16. A swatch of fabric seeded with GSR from a SA80 visualised under blue-green light

3.4.2.2 p-XRF

The light sources visualised the areas where multiple GSR particles were present which were encircled with a pen. Then, the p-XRF was aimed at these circled areas to determine whether GSR could be characterised. The p-XRF analysed 9 swatches where 5 of the swatches were seeded with GSR from a Glock 17, and 4 of the swatches were seeded with GSR from an SA80. It was shown that the p-XRF could detect GSR on 8/19 areas analysed from the 5 swatches seeded with GSR from a Glock 17 (Table 7). This is only 42% detection of the areas analysed. Additionally, barium and only background levels of lead were detected on the encircled areas. Antimony was undetected on all the swatches.

Table 7. A summary of the p- XRF results when analysing the swatches covered with GSR from a Glock 17; 2 areas per swatch were analysed which are indicated as areas 1 and 2 in the table.

Swatch	Firearm and rounds	Area	Ppm
2	Glock 17 50 rnds	1	1: not detected
			2: not detected
		2	1: not detected
			2: Ba (483 ppm)
3	Glock 17 50 rnds	1	1: not detected
			2: Ba (400 ppm)
		2	1: Ba (511 ppm)
			2: not detected
4	Glock 17 50 rnds	1	1: not detected
			2: Ba (400 ppm)
		2	1: Ba (511 ppm)
			2: not detected
7	Glock 17 50 rnds	1	1: not detected

			2: Ba (466 ppm)
		2	1: not detected 2: not detected 3: not detected
9	Glock 17 50 rnds	1	Ba (531 ppm)
		2	Ba (500 ppm)

The p-XRF could detect GSR on 5/15 areas of the 4 swatches seeded with GSR from an SA80 (table 8). This is only 33% detection of the areas analysed.

Table 8. A summary of the p- XRF results when analysing the swatches covered with GSR from an SA80; 2-3 areas per swatch were analysed which are indicated as areas 1,2, or 3 in the table.

Swatch	Firearm and round	Area	Ppm
1	SA80 65 rnds	1	not detected
		2	Ba (439 ppm)
		3	not detected
5	SA80 70 rnds	1	1: Ba (462 ppm)
			2: not detected
		2	1: not detected
			2: Ba (457 ppm) Sb (44 ppm)
6	SA80 110 rnds	1	1: not detected
			2: not detected
			3: Ba (400 ppm)
8	SA80 60 rnds	1	1: not detected
			2: not detected
			3: not detected
		2	1: not detected
			2: Ba (548 ppm)

On the areas that detected GSR, only barium was detected except for swatch 5 (area 2, attempt 2) where barium and antimony were detected.

3.5 Discussion

Overall, the results on the spatial distribution showed that there is no clear pattern in the spatial distribution of GSR on clothing of bystanders, contradicting hypothesis 1 which stated that the spatial distribution of GSR could have been used for crime reconstruction purposes. Additionally, due to this variability it was not possible to identify a pattern to the GSR distribution on bystanders to identify the standing arrangement, disproving hypothesis 2. Additionally, the results from experiment 1a demonstrates that there is no significant difference on the different days suggesting that the climatic conditions (i.e. a windy environment) are an important variable to consider, rejecting hypothesis 3 which stated that the distribution of GSR will vary depending on the external weather i.e. a day in January and a day in June.

Further, the results derived from experiment 1b further demonstrate the variability in the GSR counts on clothing of bystanders when looking at the three different runs on each day, disproving hypothesis 4 which stated that the number of GSR particulates on the clothing of a bystander would be similar when repeating the same experimental layout consecutively after each other. Additionally, there was no significant difference between the three different days, refuting hypothesis 5, which stated that the GSR count on the clothing would vary depending on the external weather. When comparing the two witnesses to each other, the results showed that witness 3 had significantly more GSR particles on the clothing compared to witness 2, disproving hypothesis 6 which stated that the GSR counts between the two witnesses would be similar. Similarly, the results showed that witness 3 had more GSR on their clothing compared to witness 2 when comparing the three different days to each other, refuting hypothesis 7 which stated that the GSR counts would vary depending on the external weather.

The results derived from experiment 2 demonstrate that GSR can persist on clothing of bystanders up to 12 hours after a shooting, supporting hypothesis 8. However, each bystander exhibited different retention times where witness 1 and 3 retained GSR up to 6 hours and witness 2 up to 12 hours, contradicting hypothesis 9 which stated that bystanders will exhibit similar GSR retention times regardless of their different daily activities.

Lastly, the results derived from experiment 3 showed that, when combined, the Crime-Lites and p-XRF can potentially visualise and characterise GSR at the crime scene, supporting hypothesis 10.

3.5.1 Spatial distribution of GSR on clothing

Experiment 1a demonstrated that GSR was recovered from most areas of the clothing across the three bystanders demonstrating that, similar to the hands of the bystander (French & Morgan, 2015), clothing can also retain GSR particulates. The literature has suggested that the distribution of GSR is affected by the location, climatic conditions and type of weapon (Fojtášek et al. 2003; Lindsay et al. 2011; Ditrich, 2012). When attempting to establish a specific pattern by performing the experiment under the same conditions, it was shown that no clear pattern could be established (refuting hypothesis 1). Additionally, comparing the three bystanders to each other further highlighted the variability of GSR deposition where there was no clear difference between the three (disproving hypothesis 2). Further, experiment 1a was performed in the same location in June and in January (in June, it was 15° C whereas in January it was 7° C) in a windy area making it possible that, even though the literature has suggested that the distribution does not significantly vary indoors compared to outdoors, that the wind is an important variable and that a less windy location could result in a more uniform distribution of particulates (Fojtášek et al. 2003). These results demonstrate that the spatial distribution of transferred GSR on clothing does not exhibit a specific pattern for crime reconstruction purposes regardless of the day (refuting hypothesis 3). These results therefore demonstrate that it is imperative that, even though all areas of the clothing should be sampled as soon as possible, interpretation should focus on identifying the meaning of detecting a particulate on the item of clothing rather than where on the item it was found.

The results from experiment 1b demonstrate similar results where there was a difficulty in establishing a pattern in the amount of GSR retained on the individual areas of the clothing of bystanders (contradicting hypothesis 4). The results demonstrated that there was a significant difference in some of the different body parts (see Results). However, even with this difference, there is no clear pattern to establish that this would reproducibly occur during a shooting. This was further highlighted when comparing the different parts of the clothing of witness 3 as there was no statistical difference. Similar results have been identified in the literature where Lindsay et al. (2013) identified the variability of GSR counts on the hands of three bystanders standing around a shooter. Additionally, Fojtasek et al. (2003) looked into the way GSR distributes when a firearm is discharged and found variable results.

This experiment was performed on three different days where three runs were performed a day in January, a day in April, and a day in July (January 7° C, April 15° C, July 19° C, but it was still overcast and windy). When comparing the three different days to each other, there was no significant difference for witness 2 or 3 between the days and the particulate count. This further demonstrates the difficulty of establishing a pattern to the standing arrangement of the witnesses standing around a shooter (supporting hypothesis 6). This could be due to the weather as the wind appears to influence the distribution of GSR particulates on the clothing of the bystanders. Additionally, this highlights the complexity of using GSR count to determine whether someone is a bystander or a shooter (French & Morgan, 2015; Lindsay et al. 2011).

Further, when looking at the individual days, it was shown that, for witness 2, there was a significant difference between the three different runs in January and the particulate. Additionally, for witness 3, there was significant difference between the three different runs in January and the particulate. However, there was no significant difference between the three different runs performed in April and in July for either witness 2 or 3. During the three different runs, the clothing items were changed to avoid GSR deposited from the previous run to affect the results so the clothing were not the reason for this increase of GSR particulates in the additional runs. This demonstrates the possibility of GSR particulates remaining in the atmosphere causing delayed deposition of GSR on the clothing as suggested by Andrassko and Peterson (1991) who showed that clothing can be contaminated by GSR due to air currents as GSR remains in the vicinity. Additionally, Fojtasek et al. (2004) showed that GSR particles stay in the air for a certain period after the shot. However, further analysis is needed to increase the sample size to determine whether this is occurring and if this should be considered when determining the meaning behind finding a particulate on an item of clothing.

Overall, when comparing the GSR count between witness 2 to witness 3, there is a statistically significant difference between the two witnesses, contradicting hypothesis 6. This could be indicative of the standing arrangement as the shooter might have inhibited some of the GSR being deposited on witness 2. This was further shown when comparing the different body parts between witness 2 to witness 3, as there was significantly more GSR detected on witness 3 than witness 2 in the left areas of clothing. This also demonstrates that, even though the distribution of GSR has been shown to be variable, that more GSR was deposited on the left of witness 3 which again could be an indication of the standing arrangement. However, considering the variability, it will still be quite difficult to use particulate count for crime reconstruction.

Additionally, when comparing the three days to each other, the results showed there was only significantly more GSR detected on witness 3 than witness 2 in January and in April (partially supporting hypothesis 7). Further, when comparing the amounts of GSR detected on the different runs between the two witnesses, the results showed there was significantly more GSR detected on witness 3 than witness 2 on runs 1 and 2. These results further support the variability of GSR deposition on clothing of bystanders and even though witness 3 appears to consistently have more GSR, there is still not sufficient evidence to indicate whether GSR can assist with distinguishing between the two bystanders.

These results from experiment 1 demonstrate the complexity of using the spatial distribution of GSR to ascertain the presence of an individual at a crime scene (French & Morgan, 2015; Lindsay et al. 2011). The implication of these results for casework is that, due to the climatic conditions, the location of the GSR particulates on the item of clothing should not (currently) be considered when interpreting the significance of detecting a GSR particulate at a particular area on the clothing. A limitation to this study is that only one firearm was tested in one location under various weather conditions. A study by Halim et al. (2010) demonstrated the variation in the release of GSR during a discharge. Further, studies to date have shown that this distribution is dependent on the location, the climatic conditions and the type of weapon used (Ditrich, 2012; Gerard et al. 2011; Fojtášek et al. 2003). As such, the spatial distribution of GSR may vary if a different firearm was used or if the experiment was performed indoors.

3.5.2 Preservation of GSR on clothing

In the persistence study, only witness 2 retained GSR up to 12 hours on the clothing, whereas witness 1 and 3 retained GSR for 6 hours or less (contradicting hypothesis 8). The results of experiment 2 demonstrate that the maximum retention time of GSR varies across the three witnesses illustrating the variation in the retention time of GSR on clothing as suggested within the literature (Dalby et al. 2010).

The variation of GSR retention between the witnesses could be due to the amount of GSR initially deposited or the level of activity of the witness. For instance, the three bystanders resumed their daily activities after the initial transfer which suggests that normal activity could cause particulates to shed at different rates as demonstrated by Kilty et al. (1975) who demonstrated that the rate of GSR loss increase when hands were washed or rubbed against clothing (contradicting hypothesis 9). However, further work is needed to hone in on the different variables and the affect these variables can have upon this shedding. Further work into establishing a timeframe would benefit by having an indication of the amount of GSR each interval including at t=0. The hindrance there is that it is difficult to deposit known amounts of GSR onto clothing.

Additionally, the literature suggests that the smoothness of the fabric needs to be considered as the jeans have a rougher surface compared to the hooded sweatshirt and thus may retain the particulates more easily (Cwiklik and Taupin, 2011; Mastruko, 2003). The literature also demonstrated that particulates tend to shed from the upper to the lower garment (Morgan et al. 2010). As such it was expected that the jeans will also more likely retain GSR for longer as it will capture GSR particulates from the upper garment. However, upon visual assessment, there did not appear to be a different but further work is needed to determine whether the fabric makes a difference.

The main limitation to this experiment was that after the initial transfer the same hooded sweatshirt and jeans were sampled at each interval. Thus, GSR particles were being lifted at the different intervals which would reduce the number of particulates present for the rest of the study. However, the results do demonstrate that GSR can be retained up to 12 hours so this limitation does not affect the results in this case. Therefore, future investigation is needed by repeating this study but re-starting the experiment at each interval i.e. performing a run where sampling occurs at 2 hours and then performing a second run where sampling occurs at the 4-hour interval. This would more accurately provide information on the maximum retention time for GSR on clothing of bystanders and allow for a more in-depth sampling methodology. Additionally, by dividing up the clothing into smaller sections, further information can be deduced from the amount of GSR being retained at the different intervals. Lastly, this study needs to be expanded to 24 hours as that is the current timeframe in place for GSR sampling (Shaw, 2013). This study only focused on a 12 hour period as there was no general consensus in the literature and this is only a preliminary study to start empirically establishing the timeframe for GSR retention (Dalby et al. 2010).

This experiment demonstrates that there is a case to be made that in some situations there may be valuable evidence present on clothing several hours after an event. It is therefore important to sample clothing even if the shooting event occurred many hours before sampling. As such, these findings may be valuable for analysis and sampling best practice procedures.

3.5.3 Analysis of GSR

The results derived from experiment 3 demonstrate that the crime-Lite 82s and the p-XRF are capable of visualising and characterising GSR particulates, supporting hypothesis 10. Specifically, for the visualisation of GSR, the results show that the blue light (which emits between 420-470 nm) can visualise more GSR particles on the swatch; but not as effectively as the blue-green light (445-510 nm). This supports the findings from Kersh et al. (2014) which determined that the optimum setting for GSR characterisation is 445-495 nm. Such an instrument is useful for casework and has already been implemented to assist with evidence collection at the scene. Using this visualisation tool could assist with sampling accuracy by indicating which areas to focus on an item but care needs to be taken when depending on collection as it is possible that particulates are still going undetected.

It was shown that only 8/19 areas (42%) on the swatches seeded with GSR from the Glock 17 (Table 7) managed to detect barium. Additionally, the swatches seeded with GSR from the SA80 (table 8) where only 5/15 (33%) of the areas analysed detected barium. In comparison, antimony was only detected once on swatch 7 (SA80) but on none of the other swatches. Lead was not detected on any of the swatches. Antimony and Lead are volatile elements which explains why GSR are undetected. However, this volatility could be a limit of the technique. The XRF can identify the different elements are present in a sample. As such, to obtain more reliable readings, the instrument might need more photons or to increase the acquisition time.

Additionally, it is possible that the barium is overlapping with the antimony due to their similar emission lines. If this is occurring, then the barium might mask the presence of antimony. However, even if the antimony is masked, barium is still the most useful element for detection as it is not commonly found. Additionally, the presence of barium can be indicative of GSR and the item should be sampled.

Further, detector geometry is a critical factor in XRF. This is a limitation with the XRF as the orientation of the sample where the x-ray is pointed at remains on the surface. As such, there may be problems with the depth of penetration of a sample. That is, if the x-ray is aimed at the barium on one side of a particulate, then there is a possibility that antimony present on the other side of the particulate goes undetected. Therefore, the quantity presented on the screen of the p-XRF might be limited to surface analysis. If detection is focused on a specific field of view, then this can present further complication such as saturation. For instance, the results from experiment 3 range between detecting 400-550 ppm. Therefore, it is possible that a point of saturation has been reached due to analysing just the one area.

Additionally, the minimum detectable quantity of each element depends on the characteristics of the equipment, the energy spectrum and the intensity of the excitation beam. It must therefore be evaluated using reference samples of known composition. This is problematic for GSR analysis as it has been difficult to establish reference samples. Thus, p-XRF might not be the most suitable for quantification as it has instant x-ray sources and will excite certain element so it could still provide information on elemental composition. Therefore, an alternative method might be more suitable for quantification. As such, this research focused on demonstrating the potential use of these instrument for GSR visualisation and characterisation. However, with known amounts a better indication of the detection limit of the Crime-Lite sources and the p-XRF could be established to determine the utility of this instrument in casework. This is shown in the literature where Flynn et al. (1998) has established that only particulate larger than 10 micrometres can be detected by the instrument and only GSR populations of 'medium' to 'high' concentrations. The studies by Berendes et al. (2006) and Janssen et al. (2015) did not look at quantification at all.

Even without the quantification problems, there are still a range of questions that need to be answered before the p-XRF can be implemented as a screening tool for GSR. For instance, there is a need to establish the minimum amount of GSR present for the p-XRF to detect it. One approach that could be undertaken is repeating this experiment using casework GSR samples of known quantities to demonstrate if low concentration of casework GSR will be detected in situ. However, as previously discussed, getting known amounts of GSR is currently not possible. Thus, the lack of known quantities of GSR appears to be a hindrance to empirically establishing a screening tool for GSR.

Overall, these three experimental studies have demonstrated the variability in the way GSR deposits and persists on clothing, and the complexity of establishing a screening tool for GSR analysis. This confirms the results in the literature which has demonstrated the same difficulties in establishing a general rule of behaviour for GSR. However, there is still value in undertaking studies grounded in casework scenarios. For example, it will enable experimental studies to offer insights that will increase the ability to interpret GSR evidence that is recovered in case investigations. As such, for more complex forms of evidence such as GSR, there is a need to properly communicate the weight of forensic findings so that the court understands the complexity of interpretating the meaning behind the evidence, and the limitations associated with the findings. Even for more complex forms of evidence, there is a need to perform empirical, reproducible studies to address (1) the robustness of interpretation and to assist the courts with assessing the weight of the findings and (2) to ensure that more complex forms of evidence are clearly communicated.

3.6 Conclusions

These experimental studies have demonstrated that casework-informed experimental studies assist in increasing our understanding of the behaviour of GSR. In this study, the complexity of the transfer and persistence processes involved was demonstrated, and the difficulty of establishing a screening tool for GSR analysis was investigated. Areas of future work were also identified that will enable empirically based interpretations of GSR evidence for crime reconstruction. Specifically:

- GSR is transferred to the clothing of all three bystanders in the vicinity of a shooter in varying degrees. However, in this study, the spatial distribution and amount of GSR particulates on clothing varies too much across these bystanders to identify a specific pattern and, appears to vary depending on the influence of external variables such as the presence and direction of the wind. It also demonstrated that there is a difference in particulate counts based on where the bystander stands. However, GSR distribution does currently appear to be too variable to establish a rule of behaviour for this.
- It is possible to detect GSR on clothing up to 12 hours after its transfer onto clothing. Detection appears to depend on the position of the witness in relation to the shooter. These findings could have implications for the current timeframes in place for GSR sampling procedures.

- When combining the Crime-Lites with the p-XRF, it was shown that they complement each other. The Crime-Lite can highlight what areas on an item to focus on whereas the p-XRF can determine whether barium is present. This provides incentives to sample for GSR by improving on sampling accuracy and reducing the number of samples collected. However, additional testing is need for quantification of GSR.

Overall, these experiments demonstrate the need to develop a method to enable known quantities of GSR to be sampled to perform empirical and reproducible studies to characterise and interpret the presence of a GSR particle. Without known quantities, it is difficult to empirically establish a timeframe. It is also difficult to determine the minimum detection limit of any screening tools. This needs to be overcome if a better insight into the behaviour of GSR is to be established.

Whilst this study represents a small scale and preliminary experiments, the findings indicate that it may be possible to provide valuable contextual information for the interpretation of trace GSR evidence detected at crime scenes. Establishing that the spatial distribution of GSR transferred onto clothing is variable and contingent on environmental factors highlights the complexity of the dynamics of GSR and the care that needs to be taken when interpreting the presence of GSR on clothing. The presence of GSR may be an indication that the wearer has discharged a firearm. However, it may also indicate that they were standing near an incident. Further studies could establish the influence of the environmental variables to provide the means of aiding crime reconstruction and identifying who was present and where they were in relation to the firearm. This study also indicates that collection protocols could consider incorporating GSR sampling of clothing seized many hours after an incident. Lastly, examining a screening tool for GSR characterisation has demonstrated the need to establish a minimum detection limit by acquiring known quantities of GSR. As such, these experimental studies have shown that there is a need to perform experimental studies for more complex forms of evidence to gain insight into the information that can be deduced and the limitations associated with such findings.

Chapter 4: The perspective of forensic scientists and criminal lawyers on the use of empirical studies to support forensic interpretation

4.1 Introduction

The release of the 2009 NAS report advocated the need to build an evidence base in forensic science to scientifically underpin forensic interpretation (National Research Council, 2009). Undertaking additional research will allow for a general body of theory to be established that can assist forensic practitioners with demonstrating how their interpretation of a particular form of evidence draws on existing evidence (McElhone et al. 2016; Morgan et al. 2009). If such research is undertaken then (like any evidence-based practice) the intended consumers of evidence need to be motivated and able to access and critique existing evidence and apply it to their everyday job (Edmond, 2013; Howes et al. 2013). However, this is not guaranteed and has not been looked at in relation to forensic science. Thus, if an evidence-based approach is to be built in forensic science, there is also a need to assess the receptivity of those responsible for handling forensic evidence i.e. forensic scientists and criminal lawyers.

This is especially important because the need to incorporate an evidence-based approach in forensic science has been met with differing opinions (Edmond et al. 2016; Koehler & Meixner, 2016; Ligertwood & Edmond, 2012). There is a contentious on-going debate within forensic science concerning the value of experimental studies to inform forensic evidence interpretation; particularly regarding the need to base interpretation on existing evidence rather than solely on professional experience (Cole, 2009; Ligertwood & Edmond, 2012; Mnookin et al. 2010). This is partially because some value lab based controlled data as a means of illustrating the strength of evidence, and others value the experience of casework scientists (because every case is different). These differing perspectives are exacerbated by the lack of willingness to hold both together and instead going for an 'either/or' approach which arguably would more robustly underpin forensic interpretation (Margot, 2011).

Thus, the purpose of this chapter is to look at the receptivity of forensic scientists and lawyers to developing an evidence base in forensic science. First, the different arguments raised in the debate will be reviewed to determine whether additional research is needed and who should undertake such research. It will also look into previous research on the receptivity of stakeholders in implementing evidence-based research into practice, and the different variables that can affect changes in these perspectives. Next, the chapter will look at the method and results of two different surveys disseminated to UK based lawyers and forensic scientists internationally on the forensic science published literature, the use of empirical studies and the need for communication and collaboration on research. Third, the results of the surveys will be reviewed and the association between different variables on the responses will be discussed.

4.1.1 Experimental studies and professional experience: the debate

Currently, there is a divide within the forensic science community on whether additional research needs to be undertaken and who needs to undertake it (Koehler & Meixner, 2016; Mnookin et al. 2010). Thus, there is a need to determine: (1) whether empirical studies should be used to support interpretations in court, and (2) who is most suited to performing such research to move towards a more evidence-based approach to illustrate the significance and/or weight of forensic evidence in a specific context.

4.1.1.1 Is additional research necessary?

Some in the forensic science community would argue that professional experience is sufficient to accurately interpret forensic evidence (Koehler & Meixner, 2016). For example, it has been argued that empirical evidence may not be entirely relevant due to the number of unknowns in many forensic investigation (Lieberman et al. 2008). That is, because studies are completed in controlled environments, the translation of their empirical findings to non-empirical situations require accurate knowledge of these unknowns (Koehler & Meixner, 2016). Additionally, even when there is research underpinning interpretation, it almost always requires adaptation, refinement, or interpretation (Edmond, 2007; Edmond, 2008). This means that there are certain aspects of forensic science that only experience can account for. Moreover, there are some within the forensic science community who believe their methods are reliable because of their wide-spread and long-running use (Köpsén & Nyström, 2012).

In contrast, others would argue that without empirical research on which to base their understanding of the meaning and significance of different forms of evidence, the value forensic evidence provides to a criminal investigation is limited (McElhone et al. 2016; Doak & Assimakopoulos, 2010; Edmond et al. 2016; Morgan et al. 2009). For instance, Edmond et al. (2012) argue that forensic interpretation is only robust if they are based on statistically-valid empirical studies, otherwise juries might give more probative weight to it than it deserves (Ligertwood & Edmond, 2012; Edmond, 2003). Additionally, even though validity is always an issue when making inferences, the accumulation of evidence and theory allows confidence to be placed in generalisations and causal attributions (Morgan et al. 2009). As such, the value that experimental studies contribute to interpretation cannot be fully overlooked as they may provide guidance to legal decision makers, investigators, and scientists involved to better understand the reliability and validity of forensic science conclusions (Koehler & Meixner, 2016).

However, a third argument is that the most robust form of interpretation is by having a balance between experimental studies and professional experience (Djulbegovic, 2017; Koehler & Meixner, 2016; Morgan, 2017). Similar arguments have been raised in medicine and policing, but these fields adopt a view where the aim of using evidence-based research is to inform practitioners on best practice to ensure the most up-to-date techniques are used (Haynes, 2002; Lum et al. 2013). This way practitioners can still draw upon experience when needed but also means that they can draw upon empirical research to support their reasoning. This was further argued in the forensic science literature where Mnookin and Cole (2011) argue that experience, training and longstanding investigatory and legal use are sources of legitimate knowledge. Additionally, Roux et al. (2012) argues for a return to problem solving forensic science which involves the development of holistic models to provide a strategy to integrate technologies, and to help scientists develop their potential to engage in a more significant way in policing, crime investigation and, in criminology. Focusing on developing this holistic model means incorporating both experience and research as this will account for two forms of knowledge: tacit and explicit knowledge (Morgan, 2017b) .

Tacit knowledge is gained implicitly by accomplishing working tasks. Explicit knowledge is a codified standard of operating systems that can be verbalised or written. Research into these different forms of knowledge found that both types are essential for a forensic scientist to perform their work whilst adding to their own knowledge base (Doak, 2008). Such a combination is especially important because it is not always possible to learn from experience in the forensic context as any mistakes that occur when the interpretation is based on solely experience often remain unknown (Koehler & Meixner, 2016). Thus, the practitioner will continue to make this mistake which does not allow space to learn and increase the accuracy of forensic interpretation in court. This is especially important because scientific validity therefore cannot be inferred from longstanding use (Ligertwood & Edmond, 2012). By allowing for both, the practitioners can consider any established theories of behaviour with particular forms of evidence whilst using their experience to acknowledge variables that are unique to a case and thus might not be accounted for by theory.

4.1.1.2 Who should undertake these empirical studies?

There has also been some debate on who should be undertaking these empirical studies. For instance, it is often seen as the responsibility of the forensic practitioner who is analysing and interpreting the findings to undertake the research necessary to support their findings (Koehler & Meixner, 2016). However, since the privatisation of forensic science in the UK, practitioners may be unable due to heavy workload and time pressure to provide results which limits the time that can be allocated to perform such research (House of Commons, 2013). Additionally, practitioners have expressed that they do not feel the need for such research as their professional experience is sufficient to interpret evidence and so may be resistant to conducting such research (Koehler & Meixner, 2016).

On the other hand, academics often have more expertise and dedicated resources (e.g. time, research design experience) to undertake such extensive research. However, Mnookin et al. (2011) argue that forensic academics, who have attempted to perform such studies, have faced limited cooperation from practitioners, as they are cautious when using external research. Similar barriers have been identified in EBP where only academics tend to perform such research and thus published work tends to use abstruse terminology and publications in ways that are not particularly user-friendly to busy practitioners (Dawson & Williams, 2009). Further, forensic science research undertaken by academics has frequently been criticised as being unrealistic thus forensically irrelevant (Koehler & Meixner, 2016). Therefore, there is a need to determine whether a more collaborative approach would be more beneficial. In policing, multiple papers have demonstrated the benefits of such a collaborative approach and emphasise the improvement on the quality and the impact of research undertaken(Guillaume, Sidebottom, & Tilley, 2012; Sherman, 2015; Sidebottom & Tilley, 2010). However, in forensic science, there are limited published case studies to demonstrate the benefit of academics and practitioners collaborating on empirical studies.

Lastly, it is often the case that the appropriate legal questions in a case are not being addressed or that there are gaps in a case that are not addressed (Cook et al. 1998a; Howes, 2015). Thus, to improve the usefulness of empirical studies, it may be helpful to collaborate and communicate with criminal lawyers (Cashman & Henning, 2012; Ledward, 2004). Such communication will enable the lawyer to convey the information they need to improve the robustness of the evidence in a case (Cashman & Henning, 2012). Additionally, by having lawyers collaborating with forensic scientists provides them with the opportunity to ask questions and gain better insight into the science behind case-based studies.

4.1.2 Receptivity of forensic scientists and lawyers

Considering these differing perspectives, one important step in moving forward with evidence-based forensic interpretation is to better understand the views of forensic scientists and criminal lawyers and their receptivity to empirical research. For instance, a similar study was undertaken in EBP by Telep and Lum (2014) who looked into the receptivity of police officers (based at three different police departments) to empirical research and evidence-based policing. The results from this study illustrated the need to improve police officers understanding on evidence-based policing. Specifically, only 25.1%, 27.8% and 48.4% of police officers understood the concept of evidence-based policing. Additionally, more than 60% of the officers did not typically read either academic or professional journals to learn about research and the effectiveness of police tactics. They also found that most of the information they are receiving comes from their own agencies and is likely policies, general orders, and procedures (or occasional legal updates about policies) which highlights the lack of communication between researchers and practitioners. Lastly, they found that only 21.5%, 7.7% and 6.1% found policing research helpful regarding police tactics. Overall, the results from this study emphasised the need to improve on the dissemination and the quality of research and to improve on communication within the policing community on EBP.

Similar studies in the receptivity of an evidence base in forensic science have not been undertaken. Thus, considering the different arguments that have been presented (outlined above), it is unclear whether these views represent the consensus of the forensic science community. That is, there is a need to determine the receptivity of lawyers and forensic scientists on the forensic science published literature, the need to undertake empirical studies, and whether there is a need to improve on communication and collaboration to increase the understanding of evidence-based forensic interpretation.

To ascertain these differing perspectives, it could be beneficial to understand the way these viewpoints alter depending on multiple background variables. For instance, given that the debate focuses on the contribution of professional experience to support interpretation, it would be beneficial to see whether an expert with more work or court experience is more likely to agree with this argument. Similarly, it would be beneficial to ascertain whether there is a divide between forensic academics and practitioners since the first tend to be more experienced in teaching and research and the latter tends to be more experienced on casework (Armstrong, 2007; National Careers Service, 2016). Overall, it tends to be the case that those who are older have more experience in a field thus age should be considered as well. Further, when looking into EBM research, a study by Metcalfe (2001) into the barriers of implementing an evidence-based approach in four different NHS therapies (dietitians, occupational therapists, physiotherapists, and speech and language therapists) showed that, 78% struggled to understand the statistical analysis, 78% found it a nuisance that the literature is not compiled in one place and 66% said that the implications for practice were not made clear. These results were interesting because only 7% of these participants had more than an undergraduate degree. It is common that those who have undertaken undergraduate degrees do not always have much experience with reviewing and analysing published literature (Mnookin et al. 2011; Quality Assurance Agency for Higher Education, 2012). Thus, considering these results, it could be beneficial to ascertain whether the perspectives of forensic scientists and criminal lawyers varied depending on education. Lastly, since admissibility criteria differs in individual countries, for example, the UK has no admissibility criteria whereas the certain states in the USA have the Daubert standard (see chapter 2 section 2.4.2), it would be valuable to ascertain the variations in perspective when comparing forensic scientists based in the UK and those abroad.

Thus, there is a need to not only gain insight into the receptivity of forensic scientists and criminal lawyers on the published literature, the use of empirical studies and communication between themselves and other stakeholders, but to also explore the effect of these different variables (age, education, employment, work and court experience, those based in the UK or not) on these perspectives.

4.1.3 Aims and Hypotheses

Overall, the different arguments (outlined above) that have been raised within the forensic science community have valid concerns. If interpretation of forensic evidence is largely based on experience, then it is difficult to demonstrate the reasoning behind the findings and is at risk of unknowingly repeating mistakes. However, forensic science often deals with limited information or unknown variables and therefore experience needs to be considered when interpreting evidence. Thus, there is a need to determine the best approach going forward to provide robust interpretation to the courts. However, understanding the receptivity of forensic scientists and criminal lawyers will provide insight into the current consensus of the forensic science community on robust interpretation.

Thus, the aim of this chapter is to investigate how much consideration the views and experience of research evidence as a foundation on which to make forensic decisions is given by forensic scientists and lawyers. To address this aim, exploratory research into the perspectives of forensic scientists and lawyers on the interpretation of forensic evidence will be undertaken. More specifically, to address these different arguments, there is a need to establish the perspectives of forensic scientists and lawyers on their current use of the published literature whether they currently use research to underpin interpretation. Further, there is a need to establish their perspectives on performing case-based studies to support interpretation. Lastly, it is important to establish the current levels of communication between forensic scientists (academics and practitioners) and criminal lawyers and their perspective on improving on such communication. Given the lack of research into the receptivity of forensic scientists and criminal lawyers and the different variables that have been looked into (see section above), it would also be beneficial to see how the following variables affect these perspectives: age, education, employment, those based in the UK or not, court experience, and work experience.

Thus, the following hypotheses are presented:

<u>For the use of the published literature</u>:

H1: Forensic scientists and criminal lawyers do not tend to find the published literature can help with forensic interpretation.

H2: Forensic scientists and criminal lawyers do tend to find the published literature can provide them with an introduction to forensic science.

<u>For the use of case-based studies</u>:

H3: Forensic scientists tend to perform their own empirical studies.

H4: Forensic scientists tend to agree that case-based studies can assist with forensic interpretation.

H5: Forensic scientists and criminal lawyers tend to agree that empirical studies help understand the general behaviour of forensic evidence.

H6: Forensic practitioners are likely to think that academics lack the practical experience to perform forensically relevant research.

<u>For communication and collaboration:</u>

H7: Criminal lawyers and forensic scientists tend to agree that there is a need to improve on communication.

H8: Forensic practitioners do not tend to collaborate with academics and lawyers do not tend to collaborate with forensic scientists.

4.2 Method

Two different surveys were created, the first was aimed at UK-based criminal lawyers and the second at forensic scientists internationally using UCL Opinio survey software. The criminal lawyers were UK-based because of the difference in the legal systems in different countries. Whereas, forensic scientists were approached internally because the problems within forensic science affect the entire community. A survey experimental design was chosen because surveys can describe the characteristics of a large population, which ensures a more accurate sample to gather targeted results in which to draw conclusions and make important decisions (ref). Surveys can be administered in many modes, such as email and social media. Additionally, surveys can be filled in anonymously which provides an avenue for more honest and unambiguous responses than other types of research methodologies.

Overall, the surveys were similar in themes and they were divided into three related sections: the use of the published literature, the use of case-based studies, and the communication between forensic scientists and lawyers (see Tables 9 and 10). The section focusing on the 'use of the published literature' was aimed at ascertaining their perspective on the current state of forensic science research and whether they use this research to assist with interpretation. The section on the 'use of case-base studies' was aimed at ascertaining their perspective on the need to perform additional empirical studies to contribute to an evidence base. Lastly, the section on communication was aimed at ascertaining their perspective on the need to and opportunities and constraints of communicating and collaborating with each other to assist with forensic science interpretation.

When composing these surveys, the questions were either posed as rating of 1 to 5, where 1 was disagree and 5 was agree, or as a multiple-choice question. Questions were posed as a rating as it has been shown to not force people to express an either-or opinion, rather allowing them to be neutral should they choose to be so (Fink, 2013). Additionally, Multiple Choice Closed-ended questions were used because they can be more specific, thus more likely to communicate similar meanings (Reja et al. 2003). Finally, the response rate is typically higher with surveys that use closed-ended question than with those that use open-ended questions. The disadvantages of using such questions is that it does not provide the respondents an opportunity to explain their reasoning. However, a few yes/no questions were added to gain insight into their opinion but this can force a respondent to provide a precise opinion as such these were minimally used (Fink, 2013). Additionally, this also does not allow them to explain further on their perspective. Lastly, the questions were crafted this way as these formats are statistically analysable. To demonstrate how the questions in the survey were formatted, see tables 9 and 10. The surveys were distributed via email, social media and legal newsletters. As such, a response rate was not calculated as it was unknown how many respondents the survey had reached. However, both the forensic scientists and the lawyers survey had a high completion rate, defined as the number of completed surveys/number of respondents who entered the survey, 97% and 93% respectively.

Table 9. The breakdown of the survey composition aimed at forensic scientists

Aim	Questions in survey
To determine the utility of the published literature for forensic scientists	Q) To what extent do you agree with the following statement: 'The published literature has assisted me with interpreting evidence on many occasions' Q) To what extent do you agree with the following statement: 'The published literature does not consider forensically realistic factors and as such is not very useful when needing assistance.' Q) To what extent do you agree with the following statement: 'The published literature is a good foundation for understanding the general behaviour of evidence but does not often help specific cases.' Q) To what extent do you agree with the following statement: 'The published literature allows me to demonstrate to the courts the validity of my results.' Q) To what extent do you agree with the following statement: 'The use of the published literature in court demonstrates that my interpretation is based on reproducible, experimental data.'
To gain insight into the forensic scientists' perspective on case-based studies	Q) To what extent do you agree with the following statement: 'Academics lack the practical experience to undertake forensically realistic research.' Q) Do you ever perform your own case experimental studies or collaborate with academics to perform such research to assist you when interpreting evidence? Q) To what extent do you agree with the following statement: 'The use of performing my own case experimental studies or collaborating with an academic has made it easier to demonstrate the validity of my interpretation in court.' Q) To what extent do you agree with the following statement: 'The use of experimental case studies is useful when trying to answer questions on the transfer and persistence of evidence.'
To gain insight into the forensic scientists' perspective on the communication between forensic practitioners and academics	Q) Do you feel that increased communication between academics and practitioners would improve upon the existing published literature? Q) How would you rate the quality of communication between yourself and academics/practitioners? Q) To what extent do you agree with the following statement: 'Experimental studies are useful for forensic interpretation but there is a need for academics and practitioners to collaborate if such an evidence base is ever to be formed.'

Table 10. The breakdown of the survey composition aimed at criminal lawyers

Aim	Questions in Survey
To determine the utility of the published literature for lawyers	Q) Have you ever looked into the published literature to augment your understanding of forensic evidence? Q) If so, how would you rate the published literature for providing the information needed to make an informed decision as to the reliability and significance of the findings of a forensic expert witness? Q) Do you find using the published literature allows forensic experts to provide more robust interpretation?
To gain insight into the lawyers' perspective on case-based studies	Q) Do you find providing case-based studies to demonstrate how an item of evidence will behave under specific conditions provides more robust forensic interpretation? Q) Would you be more confident raising doubts about experimental studies than raising doubts about an expert's professional experience? Q) To what extent do you agree with the following statement: "The use of experimental studies provide a more probabilistic and in-depth assessment of the findings." Q) To what extent do you agree with the following statement: "Experimental studies can help provide context to how evidence generally behaves but experience is valuable for understanding the variables unique to a case."
To gain insight into the lawyers' perspective on the communication between forensic scientists and lawyers	Q) Do you feel that increased communication between forensic scientists and criminal lawyers would improve upon forensic testimony? Q) How would you rate the communication between yourself and the forensic scientists that you generally deal with? Q) If empirical studies are undertaken, do you think they should be undertaken in collaboration with the legal communication to increase the utility of forensic science in cases?

The data were analysed using SPSS 22.0. When the two variables were categorical and ordinal (or interval but the variable is not normally distributed) the data were analysed using a Mann-Whitney U test. This tests whether there are differences in the ranks of the ordinal variable between the two levels of the categorical variable. In other words, will there be a difference between a randomly selected value from one group compared to the other group? When both variables were ordinal, a Spearman's rank correlation was calculated. This tests if there is a significant relationship between the ranked values of the two variables. That is, whether the two variables (when ranked) simultaneously increase/decrease or not.

To understand the effect sizes of the Mann-Whitney values, following Pallant (2007; see also Cohen, 1988;) r statistics are calculated by dividing the Z value by the square root of the total sample size. These r values are equivalent to r correlation coefficients and can be interpreted as r = 0.10 to 0.29 (small effect size), r = 0.30 to 0.49 (medium effect size) and r = 0.50 to 1.00 (large effect size) (Cohen, 1988; see also Pallant, 2007).

For the forensic scientists' survey, a logistic regression was conducted to test the relationship between one or more nominal, ordinal, interval or ratio-level independent variables and one dependent binary variable. That is, whether there was a relationship between age, employment, court experience, work experience and whether they were based in the UK or not and the use of the published literature and case-based studies, and the communication between forensic scientists. The model fits of the ordinal regressions was evaluated by using McFadden's Pseudo R2. Unlike traditional R2 values for linear regressions, pseudo R2 values tend to be considerably lower even though the fits are essentially similar. Following McFadden (1979) where he states pseudo R2 values of 0.20 to 0.40 show excellent fit we interpret pseudo R2 values of 0.20+ as showing excellent fit, 0.15-0.20 as showing very good fits, 0.10-0.15 as showing good fits and 0.05-0.10 as showing relatively good fits. For the criminal lawyers' survey, no logistic regression was run using this data due to the limited number of respondents (see below) i.e. sample size which would be insufficient to achieve stable model with an acceptable level of statistical power (Agresti, 2007).

4.3 Descriptive statistics

4.3.1 Forensic scientists

For the forensic scientists, the effect of 6 variables were investigated: age, education, employment (i.e. academic or a practitioner), whether they were based in the UK or not, work experience, and court experience (see Table 8 and Figures 10 and 11). These variables were tested against questions on the published literature, the use of case-based studies and the communication between forensic practitioners and academics to determine whether their perspective changed depending on each variable. Summary statistics of the 68 forensic scientists are in Table 11.

Table 11. The individual demographics of the 68 forensic scientists

Age	Education	UK/non-UK	Employment
Min. 25 Max. 74	2 College, 1 Vocational training, 13 Undergraduate, 31 Masters, 19 PhD, and 2 Other	33 Non-UK and 35 UK based	25 Academics and 43 practitioners

To ascertain the level of court and work experience held by the respondents, they were asked how many times they had appeared in court as an expert witness during their career and how many years of work experience they have (Figures 17 and 18). 37% of the respondents had never appeared in court as an expert witness while 35% of respondents had appeared in court over 10 times. Thus, most respondents were either new to working in forensic science or experienced.

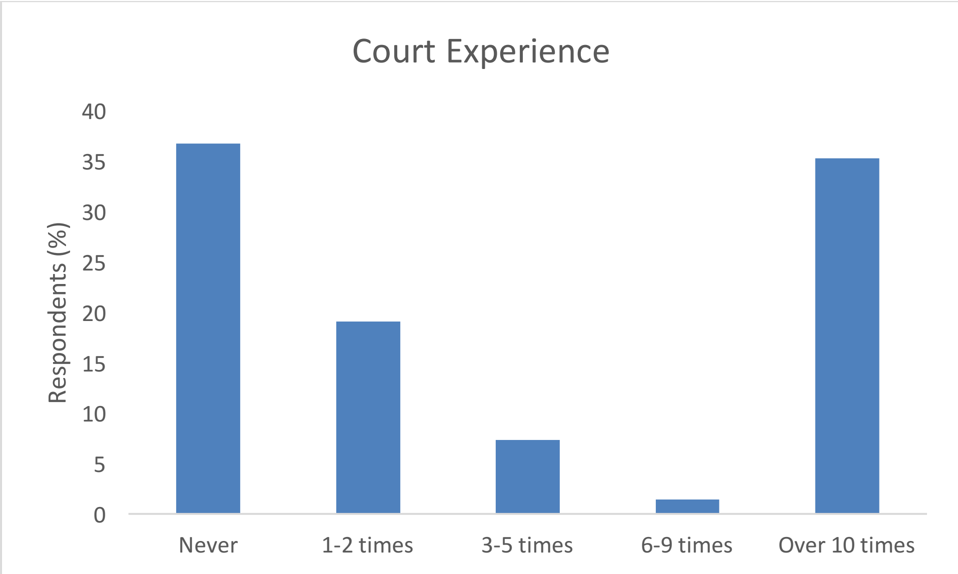


Figure 17. The breakdown of the court experience the forensic scientists' respondents have

Further, 50% of the respondents had over 10 years of experience working in the forensic science field (Figure 18) while only 10% had 0-2 years of experience. Thus, most of the respondents were experienced at handling forensic evidence.

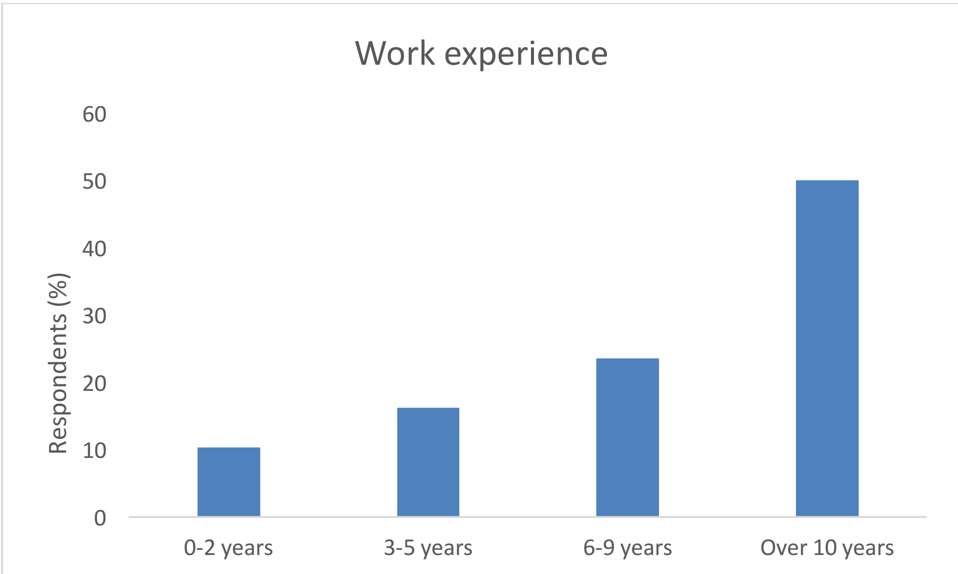


Figure 18. The breakdown of the work experience the forensic scientists' respondents have

4.3.1.1 Use of published literature

When asked whether the published literature had assisted the respondent with interpreting evidence on many occasions, 44% of respondents agreed (gave a rating of 4 or 5). When analysing this further (Table 12), Spearman's correlation suggests that the relationship between age and this question ($\rho = 0.26$, $p<0.05$) is statistically significant. Likewise, there is a statistically significant relationship between work experience and this question ($\rho = 0.25$, $p<0.05$). Further, a logistic regression demonstrated there was a significant association between age ($p < 0.05$) and whether the published literature had assisted the respondent with interpreting evidence on many occasions. The McFadden pseudo-R2 value is 0.07 which indicates a relatively good fitting model.

Table 12. The overall results between the different variables and whether the respondents use the published literature to assist with interpretation

Variable	Result
Age*	$\rho = 0.26$, $p < 0.05$
Education*	ns
Employment**	ns
UK or not**	ns
Work experience*	$\rho = 0.25$, $p < 0.05$
Court experience*	ns

* indicates a Spearmans correlation test was used; ** indicates a Mann-Whitney test was used. Additionally, ns means not-significant

When asked whether the published literature did not consider forensically relevant factors, 47% of the respondents disagreed (gave a rating of 1 or 2). When analysing this further (Table 13), there was no statistical difference between the variables and this question. However, it was shown that those not in UK are more likely to rate it higher (but not significantly more). Further, a logistic regression demonstrated there was a significant association between work experience ($p < 0.05$) and court experience ($p<0.05$) whether the published literature considered forensically relevant factors. The McFadden pseudo-R2 value is 0.05 which indicates a relatively good fitting model.

Table 13. The overall results between the different variables and whether the respondents agreed that the forensic literature is not realistic

Variable	Result
Age*	ns
Education*	ns
Employment**	ns
UK or not**	ns
Work experience*	ns
Court experience*	ns

* indicates a Spearmans correlation test was used; ** indicates a Mann-Whitney test was used. Additionally, ns means not-significant

When asked whether the published literature provides a good foundation for understanding the behaviour of evidence, 40% of the respondents agreed. When analysing this response further (Table 14), there was a statistical difference between if they were from the UK or not ($Z=-2.33$, $p < 0.05$) and this question. Further, there was no statistical difference between the other variables. However, it was shown that, for employment, academics did rate it higher (but not significantly more). When examined using a logistic regression, there was a significant association between work experience ($p < 0.05$) and those based in the UK or not ($p<0.05$) and whether the published literature provides a good forensic foundation. The McFadden pseudo-R2 value is 0.07 which indicates a relatively good fitting model.

Table 14. The overall results between the different variables and whether the respondents agreed that the forensic literature provides a good foundation to understanding the behaviour of evidence

Variable	**Result**
Age*	ns
Education*	ns
Employment**	ns
UK or not**	$Z=-2.33$, $p < 0.05$
Work experience*	ns
Court experience*	ns

* indicates a Spearmans correlation test was used; ** indicates a Mann-Whitney test was used. Additionally, ns means not-significant

When asked whether the published literature can assist with demonstrating the validity of interpretation, 46% of respondents agreed (gave a 4 or 5). When analysing this response further (Table 15), a logistic regression demonstrated that there is a significant association between education ($p<0.05$) and whether the published literature can assist with demonstrating the validity of interpretation. The McFadden pseudo-R2 value is 0.05 which indicates a relatively good fitting model.

Table 15. The overall results between the different variables and whether the respondents agreed that the published literature can demonstrate the validity of interpretation

Variable	**Result**
Age*	ns
Education*	ns
Employment**	ns
UK or not**	ns
Work experience*	ns
Court experience*	ns

* indicates a Spearmans correlation test was used; ** indicates a Mann-Whitney test was used. Additionally, ns means not-significant

When asked whether use of the published literature in court demonstrates that my interpretation is based on reproducible, experimental data, 48% of respondents agreed (gave a 4 or 5). As shown in Table 16, spearman's correlation and Mann-Whitney found no relationship between the variables and the question.

Table 16. The overall results between the different variables and whether the respondents agreed that the use of the published literature in court demonstrates that my interpretation is based on reproducible, experimental data

Variable	Result
Age*	ns
Education*	ns
Employment**	ns
UK or not**	ns
Work experience*	ns
Court experience*	ns

* indicates a Spearmans correlation test was used; ** indicates a Mann-Whitney test was used. Additionally, ns means not-significant

4.3.1.2 Use of case-based studies

When asked whether academics lack the practical experience to undertake forensically realistic research, 44% of respondents agreed (gave a 4 or 5). When analysing this response further (Table 17), a logistic regression found that there is a significant association between court experience ($p<0.05$) and whether academics lack the practical experience to undertake forensically realistic research. The McFadden pseudo-R2 value is 0.04 which indicates a relatively good fitting model.

Table 17. The overall results between the different variables and whether the respondents agreed that lack the practical experience to undertake forensically realistic research

Variable	Result
Age*	ns
Education*	ns
Employment**	ns
UK or not**	ns
Work experience*	ns
Court experience*	ns

* indicates a Spearmans correlation test was used; ** indicates a Mann-Whitney test was used. Additionally, ns means not-significant

When asked whether they ever perform your own case experimental studies or collaborate with academics to perform such research to assist you when interpreting evidence, 82% of respondents said they did (48.53% said on occasion and 33.82% said quite frequently). When analysing this further (Table 18), there was a significant difference between age ($\rho = 0.32$, $p < 0.01$), education ($\rho = 0.38$, $p < 0.01$), employment ($Z=2.10$, $p < 0.05$), and work experience ($\rho = 0.35$, $p < 0.01$). Further, a logistic regression demonstrated that there is a significant association between court experience ($p<0.05$) and a forensic scientist is based in the UK or not ($p<0.05$) and whether they ever perform your own case experimental studies or collaborate on them. The McFadden pseudo-R2 value is 0.05 which indicates a relatively good fitting model.

Table 18. The overall results between the different variables and whether they ever perform your own case experimental studies or collaborate with academics to perform such research to assist you when interpreting evidence

Variable	Result
Age*	$\rho = 0.32$, $p < 0.01$
Education*	$\rho = 0.38$, $p < 0.01$
Employment**	$Z=2.10$, $p < 0.05$
UK or not**	ns
Work experience*	$\rho = 0.35$, $p < 0.01$
Court experience*	ns

* indicates a Spearmans correlation test was used; ** indicates a Mann-Whitney test was used. Additionally, ns means not-significant

When asked whether the use of performing my own case experimental studies or collaborating with an academic has made it easier to demonstrate the validity of my interpretation in court, 48% of respondents agreed (gave a 4 or 5). When analysing this further (Table 19), there was a significant difference between forensic scientists based in the UK and not ($Z= 2.0$, $p < 0.05$), $r = .29$ (small to medium)). Further, a logistic regression found that there is a significant association between employment ($p<0.05$) and work experience ($p<0.05$) and whether the use of performing my own case experimental studies or collaborating with an academic has made it easier to demonstrate the validity of my interpretation in court. The McFadden pseudo-R2 value is 0.17 which indicates a very good fitting model.

Table 19. The overall results between the different variables and whether the use of performing my own case experimental studies or collaborating with an academic has made it easier to demonstrate the validity of my interpretation in court

Variable	Result
Age*	ns
Education*	ns
Employment**	ns
UK or not**	Z= 2.0, $p < 0.05$
Work experience*	ns
Court experience*	ns

* indicates a Spearmans correlation test was used; ** indicates a Mann-Whitney test was used. Additionally, ns means not-significant

When asked whether the use of experimental case studies is useful when trying to answer questions on the transfer and persistence of evidence, 75% of respondents agreed (gave a 4 or 5). When analysing this response further (Table 20), a logistic regression demonstrated that there is a significant association between court experience ($p<0.05$) and work experience ($p<0.05$) and whether the use of experimental case studies is useful when trying to answer questions on the transfer and persistence of evidence. The McFadden pseudo-R2 value is 0.17 which indicates a very good fitting model.

Table 20. The overall results between the different variables and whether the use of experimental case studies is useful when trying to answer questions on the transfer and persistence of evidence

Variable	Result
Age*	ns
Education*	ns
Employment**	ns
UK or not**	ns
Work experience*	ns
Court experience*	ns

* indicates a Spearmans correlation test was used; ** indicates a Mann-Whitney test was used. Additionally, ns means not-significant

4.3.1.3 Communication and collaboration

When asked whether they felt that increased communication between academics and practitioners would improve on the published literature, 97% agreed it would. However, when they had to rate the quality of communication between themselves and academics/practitioners, 44% of respondents rated it high (gave a 4 or 5). As shown in Table

21, spearman's correlation and Mann-Whitney found no relationship between the variables and the question.

Table 21. The overall results between the different variables and how they would rate the quality of communication between yourself and academics/practitioners

Variable	Result
Age*	ns
Education*	ns
Employment**	ns
UK or not**	ns
Work experience*	ns
Court experience*	ns

* indicates a Spearmans correlation test was used; ** indicates a Mann-Whitney test was used. Additionally, ns means not-significant

When asked whether experimental studies are useful for forensic interpretation but there is a need for academics and practitioners to collaborate, 90% of respondents agreed (gave a 4 or 5). When analysing this further (Table 22), there was a significant difference between employment ($Z=-2.88$, $p < 0.01$) and this question, where academics rated it higher. Likewise, there was a significant difference between UK or not ($Z= 2.45$, $p < 0.05$) and this question, where not UK rated higher. Further, a logistic regression demonstrated that there is a significant association between employment ($p<0.05$) and whether experimental studies are useful for forensic interpretation but there is a need for academics and practitioners to collaborate. The McFadden pseudo-R2 value is 0.16 which indicates a very good fitting model.

Table 22. The overall results between the different variables and whether experimental studies are useful for forensic interpretation but there is a need for academics and practitioners to collaborate

Variable	Result
Age*	ns
Education*	ns
Employment**	$Z=-2.88$, $p < 0.01$
UK or not**	$Z= 2.45$, $p < 0.05$
Work experience*	ns
Court experience*	ns

* indicates a Spearmans correlation test was used; ** indicates a Mann-Whitney test was used. Additionally, ns means not-significant

4.3.2 Criminal lawyers

For the criminal lawyers, the effect of 5 variables were investigated: age, education, employment (i.e. academic or a practitioner), work experience, and court experience (see Table 23 and Figures 19 and 20). These variables were tested against questions on the published literature, the use of case-based studies and the communication between criminal lawyers and forensic scientists to determine whether their perspective changed depending on each variable. Summary statistics of the 28 criminal lawyers are presented in table 23.

Table 23. The individual demographics of the 28 criminal lawyers

Age	Education	Employment
Min. 23 Max. 63	8 Undergraduate, 15 Masters, and 5 Other	19 Barristers and 8 Solicitors (1 N/A)

To ascertain the level of court and work experience held by the respondents, they were asked how many times they had appeared in court during their career and how many years of work experience they had (Figures 19 and 20). It was shown that 43% of respondents had never appeared in court (Figure 19). Additionally, 36% of respondents had appeared in court over 10 times. Thus, most respondents were either new to law or experienced.

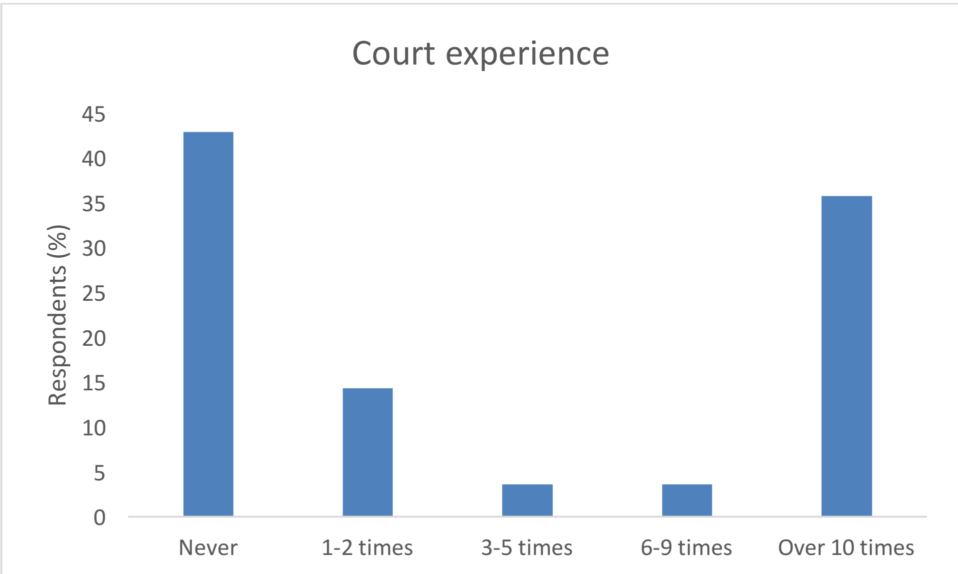


Figure 19. The breakdown of the court experience the criminal lawyers' respondents have

Further, 54% of respondents had over 10 years of experience working in the forensic science field (Figure 20) while only 14% had 0-2 years of experience. Thus, most of the respondents were experienced at handling forensic evidence.

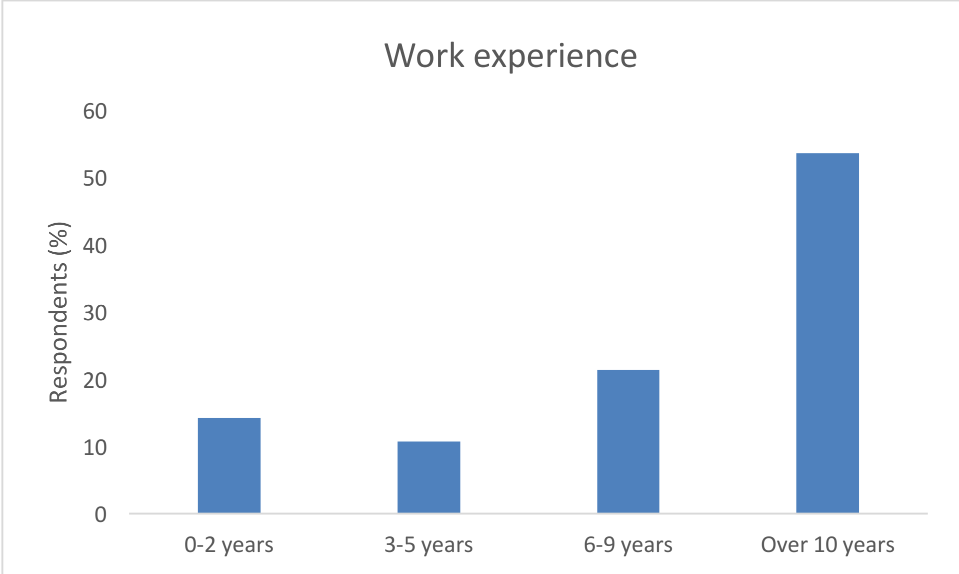


Figure 20. The breakdown of the work experience the forensic scientists' respondents have

4.3.2.1 Use of published literature

When asked whether they had accessed the published literature to increase their understanding of forensic evidence, 69% said they did (24% said quite frequently and 45% occasionally). When analysing this further (Table 24), there is a statistical difference between education and whether lawyers accessed the published literature ($Z= -3.21$, $p < 0.01$) where Masters are higher ranked so they rate 24 higher; $r = -0.68$ (large effect size). Additionally, there is a statistically significant difference between employment and using the published literature ($Z= -2.36$, $p < 0.05$), where barristers use the literature more often, $r = -0.47$ (which is equivalent to a medium to large effect size).

Table 24. The overall results between the different variables and whether they had accessed the published literature to increase their understanding of forensic evidence

Variable	**Results**
Age*	ns
Education**	$Z= -3.21$, $p < 0.01$
Employment**	$Z= -2.36$, $p < 0.05$,
Work experience*	ns
Court experience*	ns

* indicates a Spearmans correlation test was used; ** indicates a Mann-Whitney test was used. Additionally, ns means not-significant

Expanding on this, respondents were asked to rate the published literature for providing the information needed, where 21% rated it high (gave a 4). As shown in Table 25, spearman's correlation and Mann-Whitney found no relationship between the variables and the question.

Table 25. The overall results between the different variables and rate the published literature for providing the information needed

Variable	Result
Age*	ns
Education**	ns
Employment**	ns
Work experience*	ns
Court experience*	ns

* indicates a Spearmans correlation test was used; ** indicates a Mann-Whitney test was used. Additionally, ns means not-significant

When asked whether using the published literature allows forensic experts to provide more robust interpretation, where 72% agreed (24% said quite frequently and 48% said occasionally). When analysing this response further (Table 26), there is a statistical difference between employment and whether they agree the published literature assist with interpretation ($Z = -2.1$, $p < 0.05$) where solicitors were more likely to agree. Additionally, there is a statistical difference between court experience and the use of the published literature ($\rho = 0.35$, $p < 0.05$) where those with less court experience would agree.

Table 26. The overall results between the different variables and whether using the published literature allows forensic experts to provide more robust interpretation

Variable	Result
Age*	ns
Education**	ns
Employment**	$Z = -2.1$, $p < 0.05$
Work experience*	ns
Court experience*	$\rho = 0.35$, $p < 0.05$

* indicates a Spearmans correlation test was used; ** indicates a Mann-Whitney test was used. Additionally, ns means not-significant

4.3.2.2 Use of case-based studies

When asked whether they agree case-based studies help demonstrate how an item of evidence will behave to support forensic interpretation, where 10% agreed (3% said definitely and 7% most of the time). When analysing this response further (Table 27), there was no significant difference between the variables and whether case-based studies to support interpretation.

Table 27. The overall results between the different variables and whether they provide case-based studies to demonstrate how an item of evidence will behave to support forensic interpretation

Variable	**Result**
Age*	ρ = -0.19, p>0.05
Education**	Z= -1.06, p > 0.05
Employment**	Z = .58, p > 0.05
Work experience*	ρ = -0.37, p > 0.05
Court experience*	ρ = -0.26, p > 0.05

* indicates a Spearmans correlation test was used; ** indicates a Mann-Whitney test was used. Additionally, ns means not-significant

When asked whether they would be more confident raising doubts about experimental studies than raising doubts about an expert's professional experience, 45% agreed. When analysing this response further (Table 28), there was a significant difference between education ($Z = -2.03$, $p < 0.05$), where masters rated it higher, r= -.46 (which is the equivalent to a medium to large effect size).

Table 28. The overall results between the different variables and whether they would be more confident raising doubts about experimental studies than raising doubts about an expert's professional experience

Variable	**Result**
Age*	ns
Education**	Z = -2.03, p < 0.05
Employment**	ns
Work experience*	ns
Court experience*	ns

* indicates a Spearmans correlation test was used; ** indicates a Mann-Whitney test was used. Additionally, ns means not-significant

When asked whether the use of experimental studies provide a more probabilistic and in-depth assessment of the findings, 38% agreed (gave a 4 or 5). When analysing this response further (Table 29), there was a statistical difference between employment ($Z = -1.96$, $p < 0.05$) where barrister rated it higher, r=.45 (medium to large). Likewise, there was a significant difference between age ($\rho = 0.43$, $p < 0.05$) and work experience ($\rho = 0.42$, $p < 0.05$) and their perspective on the use of experimental studies.

Table 29. The overall results between the different variables and whether the use of experimental studies provide a more probabilistic and in-depth assessment of the findings

Variable	Result
Age*	ρ =0.43, $p < 0.05$
Education**	ns
Employment**	$Z = -1.96$, $p < 0.05$
Work experience*	ρ =0.42, $p < 0.05$
Court experience*	ns

* indicates a Spearmans correlation test was used; ** indicates a Mann-Whitney test was used. Additionally, ns means not-significant

When asked whether experimental studies can help provide context to how evidence generally behaves but experience is valuable for understanding the variables unique to a case, 45% agreed (gave a 4 or 5). When analysing this response further (Table 30), there was no statistical difference between age, education, employment, work and court experience.

Table 30. The overall results between the different variables and whether experimental studies can help provide context to how evidence generally behaves but experience is valuable for understanding the variables unique to a case

Variable	Result
Age	ns
Education	ns
Employment	ns
Work experience	ns
Court experience	ns

* indicates a Spearmans correlation test was used; ** indicates a Mann-Whitney test was used. Additionally, ns means not-significant

4.3.2.3 Communication and collaboration

When asked whether they felt the increased communication between forensic scientists and criminal lawyers would improve forensic testimony, 90% agreed it would. However, when asked to rate the communication between themselves and forensic scientists, only 34% gave it a high rating (4 or 5). Lastly, when asked whether they thought that empirical studies should be undertaken in collaboration with the legal community, 62% agreed that it should.

Table 31. The overall results between the different variables and rating the communication between themselves and forensic scientists

Variable	Result
Age*	ns
Education**	ns
Employment**	ns
Work experience*	ns
Court experience*	ns

* indicates a Spearmans correlation test was used; ** indicates a Mann-Whitney test was used. Additionally, ns means not-significant

4.4 Discussion

While the 2009 NAS report, as well as some researchers and practitioners, have been advocating for the need to build evidence-based forensic interpretation (Council, 2009; McElhone et al., 2016; Morgan et al., 2009), whether this can occur in practice depends on a number of factors, a major one being the receptivity of the forensic science community to research and analysis. When reviewing the results of the surveys, it can be identified that that these issues remain timely. For instance, when exploring the use of the published literature, the results showed that most forensic scientists and criminal lawyers do not tend to find the published literature can support interpretation, supporting hypothesis 1. Nevertheless, further clarification on the specific barriers that are inhibiting the use of the published literature need to be established. However, the results did show that forensic scientists and criminal lawyers tend to find the published literature can help increase forensic understanding, refuting hypothesis 2.

Further, the results showed that most forensic scientists do tend to perform their own case-based studies, supporting hypothesis 3. Additionally, forensic scientists do tend to agree that case-based studies can assist with forensic interpretation, supporting hypothesis 4. The results also that forensic scientists tend to agree that empirical studies help understand the general behaviour of forensic evidence (partially supporting hypothesis 5). However, criminal lawyers do not tend to agree and often feel that empirical studies are easier to place doubt on than professional experience. Therefore, lawyers possibly do not understand the role of experimental studies and the need for an evidence-based approach in forensic science. Moreover, when reviewing the perspective of forensic scientists and lawyers on the use of case based studies, the literature identified that there is a concern that academics lack the practical experience to perform forensically relevant research. However, the results showed that most respondents appear to feel this way regardless of employment (disproving hypothesis 6).

Therefore, since both parties feel this way, it is possible that with increased collaboration, academics could undertake more forensically relevant research to assist with building an evidence base.

Lastly, criminal lawyers and forensic scientists tend to agree that there is a need to improve on communication, supporting hypothesis 7. However, the results also showed that most forensic scientists and lawyers wouldn't rate their current level of communication as high. Additionally, most forensic scientists do tend to think that there is a need to improve on collaboration with academics. Whilst, most lawyers do not tend to agree that they should improve collaborations with forensic scientists, partially refuting hypothesis 8. Thus, to improve collaborations, there is a need to determine a way to open the lines of communication between these parties and identify any hindrances in place.

4.4.1 Use of published literature

When exploring the perspective of forensic scientists on the use of the published literature, the results demonstrated that only 44% of them had frequently use the literature to assist them with interpreting results (partially supporting hypothesis 1). This perspective tended to vary depending on age and work experience where the more work experience (and thus the older) a forensic scientist had, the less likely they were to use the literature for interpretation. That is, a more experienced forensic scientist appears to be more likely to rely on their professional experience to interpret results. Additionally, only 48% of forensic scientists agreed that the published literature can be used to demonstrate interpretation is based on empirical studies. Thus, there is a need to identify the barriers that are inhibiting the use of the literature. This is especially important because the results did identify that only 47% of forensic scientist agreed that the published literature does not consider forensically relevant factors. This means that it is not necessarily the quality of research that reduces the use of the published literature though forensic relevance of research is still an issue that needs to be further investigated.

Additionally, when exploring the perspective of criminal lawyers on the use of the published literature, 72% of criminal lawyers agreed that using the literature provides more robust interpretation (partially refuting hypothesis 1). This perspective tends to vary depending on employment and court experience where barristers (who are the ones who attend court) were more likely to agree with this. Therefore, it could be of value to present published literature to support interpretation. However, further work needs to be undertaken to determine whether such studies would combine with professional experience and what the balance between the two to support robust interpretation would look like.

Further, only 40% of forensic scientists did agree that the literature provides them with an introduction to forensic science (partially refuting hypothesis 2). This perspective varied depending on whether the forensic scientist was based in the UK or not where the non-UK forensic scientists were more likely to agree. This is possibly due to privatisation in the UK as the literature has argued that, due to time pressure and a heavy workload, they do not have time to undertake additional research (House of Commons, 2013). This could also be depending on their background, for instance, the respondents were asked what the highest degree was that they had obtained, but the survey did not require them to specify the subject of the degree. So, it is possible that when comparing those with undergraduate degrees in harder sciences to those with other undergraduate degrees, that they might have different perspectives on the literature.

When exploring the perspective of criminal lawyers on the use of the published literature to provide a good foundation into forensic science, it was shown that 69% of criminal lawyers agreed (partially supporting hypothesis 2). This perspective tends to vary depending on employment where barristers were more likely to use the literature and education where those with a Masters were more likely to. For employment, this variation could be due to the experience of the lawyer with handling forensic evidence and accessing the published literature. For education, this variation could be because undergraduates do not tend to access the published literature whereas postgraduates do. Thus, it is possible that those without a Masters are not sure where to find the right information or what to search for. This could possibly be because only 21% of criminal lawyers found that the published literature could provide the information that the lawyer needed. Similarly, a study by Metcalfe (2001) identified that one barrier to implementing an evidence-based approach was that the literature could not be found in place. Therefore, determining a more systematic way for practitioners and lawyers to review the literature might help with increasing its use.

4.4.2 Use of case-based studies

When exploring the perspective of forensic scientists on the use of case-based studies, it was shown that 82% of forensic scientists tend to perform their own studies (supporting hypothesis 4). When analysing these results further, this perspective appeared to differ depending on age, education, employment and work experience. This shows that there appears to be a considerable amount of fluctuation in the perspectives on the utility of case-based studies and could be because there is no cohesion between stakeholders, causing the research landscape to be uncoordinated as there is minimum collaboration (or agreement) in research (Silverman, 2011; Chief Scientific Officer, 2015).

However, when looking into the use of experimental studies to assist with forensic interpretation, 48% of forensic scientists agreed that such studies can help demonstrate the validity of interpretation (supporting hypothesis 5). The results showed that this perspective differed between those in the UK or not where those not in the UK tend to agree with it more. Additionally, further analysis showed that this perspective also tended to differ depending on employment and work experience where those with less work experience and academics tend to agree with this. These variables demonstrate that there are mixed feelings on whether an evidence-based approach should be implemented. This is especially important because, without coming to a consensus on the best approach forward, the robustness of interpretation remains questionable. For instance, the literature has argued that without empirical evidence, the value of forensic evidence is limited (McElhone et al. 2016; Doak and Assimakopoulos, 2007; Edmond et al. 2016; Morgan et al. 2009). Additionally, it has been argued that forensic interpretation is only robust if based on empirical studies otherwise the jury might give it more weight (Edmond, 2012). However, others have advocated that experience is sufficient (Koehler & Meixner, 2016). Having such mixed receptivity means that there is a need to expand on this work to identify the reasoning behind these perspectives to try, and find a compromise and reach a consensus on what the forensic science community should do to address the concerns raised by the NAS report. This was supported by the literature which has argued the need for both with a view to include two different types of learning: tacit and explicit (Doak, 2008). This was further supported by the results as 45% of criminal lawyers also agreed that experimental studies help provide context to how evidence haves but experience is still invaluable for interpretation.

Further, 75% of forensic scientists did tend to agree that case-based studies can help with understanding the transfer and persistence of evidence. This is important as this is when evidence gets more complicated as was highlighted in the previous chapter. However, only 10% of criminal lawyers tend to agree that case-based studies can be used to demonstrate how an item of evidence behaves (contradicting hypothesis 5). Additionally, only 38% of criminal lawyers agreed that empirical studies can provide a more probabilistic assessment for interpretation. This perspective differed depending on employment, age and work experience where barristers, those with more work experience and older were less likely to agree. These results could be because lawyers do not tend to participate with empirical studies and it is possible that lawyers do not fully understand the role of experimental studies to build an evidence base. This was illustrated as only 45% of criminal lawyers tend to agree that they felt more confident raising doubt on empirical studies than on experience. This differed depending on education where those with a Masters tend to agree with this more. These results further support the literature as the NAS report argued that lawyers and judges often have insufficient training and background in scientific methodology. This often leads to a failure to comprehend approaches employed by different forensic disciplines and reliability of forensic evidence (Ledward, 2004; Bolton-King, 2015; Wheate, 2010). As such, these results and the literature highlight that improved communication between forensic scientists and lawyers could increase the forensic understanding of lawyers by providing them with the opportunity to ask questions (ASCLD, 2009; Cashman, 2012).

Lastly, when considering the perspective of forensic scientists and whether academics lack the practical experience to undertake forensically relevant research, where 44% tend to agree. However, there was no significant difference between employment as such it appears this a concern for both academics and practitioners, contradicting hypothesis 5. Additionally, these results contradict the literature which have argued that academics tend to not provide forensically relevant research (Koehler and Meixner, 2016) and has emphasised that academics have faced limited co-operation from practitioners (Mnookin, 2011). Further, a logistic regression showed that those with more court experience ($p<0.05$) do tend to agree with this statement. Thus, it is possible that practitioners with more court experience might agree that the research is not forensically relevant. Considering there have been mixed reviews to the use of the published literature and the use of case-based studies, it might be that it is more the use of research instead of who is undertaking the research. However, there is still a need to determine whether empirical studies are needed and who will undertake them.

4.4.3 Communication and collaboration

When investigating the communication of forensic scientists, 97% of forensic scientists tend to agree that there is a need to improve communication between forensic practitioners and academics (partially supporting hypothesis 6). Additionally, 90% of criminal lawyers agreed there is a need to increase communication between lawyers and forensic scientists (supporting hypothesis 6. Further, when forensic scientists and lawyers had to rate their current communication level, only 44% and only 34% respectively would rate their communication as high. These results demonstrate that forensic scientists and lawyers do agree with the literature that there is a need to improve communication. However, it also emphasises that, in practice, this communication is currently being hindered.

Further, when analysing whether forensic practitioners should collaborate with academics, 90% of the forensic scientists' respondents agreed (supporting hypothesis 7). However, there was a significant difference between employment where academics tend to agree with this more than practitioners. Additionally, this tend to differ between those based in the UK or not where those not in the UK agreed with this more. Further, 62% of criminal lawyers agreed that there is a need for empirical studies to be taken in collaboration with lawyers. Thus, there is a need to determine ways to open the lines of communication between these stakeholders to ensure that the differing perspective on using evidence-based interpretation and undertaking research can be properly understood and a way to move forward through collaboration can be instigated.

Overall, the results from these preliminary surveys demonstrate that there are mixed perspectives concerning the use of the published literature and case-based studies to support interpretation where this perspective mainly varied depending on work and court experience. However, these results are limited in information as the questions were designed with close-ended questions to ensure maximum response and completion rates. Thus, there is a need to gain further insight into their perspective on (1) other ways they might address the lack of scientific underpinning in forensic science and (2) to find a balance between using professional experience and empirical studies to underpin interpretation. To do this, the next steps in future work should focus on disseminating surveys on similar topics using open ended questions which will give them the opportunity to provide their reasoning to their answers. This would assist with more concretely identifying their perspectives on the debate on professional experience and empirical studies to support interpretation. Additionally, the results could see a difference between work and court experience on multiple occasion. However, in future work, it would be worthwhile to gain further insight into the background of the respondents to determine the effect of the variables analysed in more detail. For instance, for their employment, they were grouped either as an 'academic' or a 'practitioner'. However, this assumes homogeneity when it is common for practitioners to go into academia after a certain amount of years as a practitioner and for those in academia to move into casework.

Further, the results from this study identified that most forensic scientists do not use the literature. This is useful insight as it allows future work to identify why forensic scientists are apprehensive about using the literature. By identifying these barriers, it will be possible to determine a way to overcome them. Additionally, the results did show that most forensic scientists do perform their own case-based studies. This demonstrates that experimental studies can add value to interpretation. However, further work should determine under which circumstances such studies are undertaken and who undertakes them.

Lastly, the results from this survey have also demonstrated that communication between forensic academics, practitioners and criminal lawyers is not very common and there is a need to open these lines of communication to increase collaboration between these parties. However, further work should focus on identifying ways to assist with developing this communication as it remains unclear why communication is minimal. Therefore, the results from this chapter have identified a basis for further work to gain better insight into the perspectives of criminal lawyers, forensic practitioners and academics on the use of experimental studies and the published literature to start addressing the on-going debate.

4.5 Conclusion

These responses collected from the surveys have demonstrated that the debate regarding the use of professional experience and empirical studies to underpin interpretation remains timely. Such differing perspectives makes it difficult to determine the best approach forward to addressing the concerns raised by the NAS report, and establishing a scientific underpinning in forensic science. This is especially true given that it has been shown that most forensic scientists and lawyers do not tend use the current published literature nor do they collaborate on case-based studies. Thus, without coming to a consensus on the use of empirical studies, it is unlikely that either (1) any additional research will be collectively used to establish the scientific underpinning in forensic science nor (2) that the usefulness of forensic science research to underpin interpretation will improve. Specifically:

- Most forensic scientists and lawyers do not appear to use the published literature to support interpretation. Possible explanations for this are that only 47% of forensic scientists agreed that the literature is forensically relevant. Additionally, only 29% of lawyers found the information they needed. Thus, further work needs to identify these barriers that are limiting the use of the literature and implement ways of overcoming them.
- Most forensic scientists do tend to perform their own case-based studies. However, this perspective varied tremendously across the variables indicating that there are differing perspectives in the community on whether empirical studies should support interpretation. Thus, there is a need to gain further insight into these perspectives before an approach forward can be determined.
- Even though most forensic scientists and lawyers tend to agree there is a need to improve on communication, most of them do not rate their current communication as high. Thus, there is a need to determine a way to open the lines of communication to allow for improved collaboration.

Whilst these results represent an exploratory study, the findings do indicate the value of gaining insight into these differing opinions as a first step to achieving a solution to this debate. Establishing the lack of use of the published literature to support interpretation demonstrated that there is a need to determine the barriers in place that are causing this. Additionally, it appears that most forensic scientists do perform their own-case based studies. However, their perspective on whether such studies assist with interpretation needs to be better established.

Further research should therefore focus on gaining more insight into these perspectives by expanding on these surveys with more open-ended question, which will provide the respondents with an opportunity to clarify their answers.

Chapter 5: The role of communication in evidence-based interpretation

5.1 Introduction

Thus far, this thesis has advocated the need for an evidence-based approach to underpin forensic interpretation. This was first done by demonstrating the need to perform experimental studies to address the lack of scientific underpinning in forensic science, even for complex forms of evidence such as gunshot residue. Then, this thesis investigated the receptivity of criminal lawyers and forensic scientists by gaining insight into their perspective on the current published literature and the need to perform empirical studies. However, the results from these two experimental chapters demonstrate the complexity of establishing an evidence base in forensic science due to (1) the complexity of interpreting evidence and (2) the hesitance of the forensic science community to adopt an evidence based approach. The hesitance of the forensic science community is to be expected as reviewing the literature from the medical and policing fields has highlighted similar barriers to implementing an evidence-based approach (Djulbegovic, 2017; Greenhalgh et al. 2014; Lum et al. 2013; Telep & Lum, 2014). Regardless, these fields have also demonstrated that an evidence-based approach does allow practitioners to underpin their findings with the most accurate and up-to-date research (Bensing, 2000; Dawson & Williams, 2009). Thus, even if additional research highlights the complexity of interpretation, gaining additional insight into how evidence behaves can assist with placing weight on the forensic findings (McElhone et al. 2016). To assist with establishing scientific underpinning in forensic science, it would be beneficial to have a research culture in forensic science (Mnookin, 2011). To develop such a culture, there is a need for forensic scientists and lawyers to communicate and collaborate on casework and research. That is, they need to have a legal and scientific understanding to identify the areas that need reform to ensure research is forensically relevant. As such, the results of this thesis have identified two major areas of communication that require improvement: (1) general communication between forensic scientists, criminal lawyers and policymakers on casework and (2) communication between forensic practitioners, academics and criminal lawyers of forensic science research.

Improving these two areas of communication is essential because forensic science is in a distinctive area where it exists within the legal-science interface. However, the communication between lawyers and forensic scientists is hindered as they do not appear to speak a common language which obstructs conversation across law/science borders (McCartney & Cassella, 2011). Therefore, criminal lawyers and forensic scientists need to overcome the challenges associated with communication and collaboration to ensure that: (1) the evidence in criminal proceedings is placed under sufficient scrutiny, (2) that forensic scientists and lawyers are properly educated and trained to fulfil their responsibilities to the courts, and (3) that the research undertaken is forensically relevant (Chief Scientific Officer, 2015; Silverman, 2011).

This communication is further complicated because, even though law and science share a common aim as they are both trying to establish the criminal scenario, they have different approaches in doing so (Howes, 2015; Jasanoff, 1995; Wheate, 2006). A forensic scientist will establish the facts by analysing scientific evidence in an unbiased, impartial manner to assist with a criminal investigation (Linacre, 2013). This approach focuses more on a 'testing and development' method where the published literature is used as a platform for additional research to build upon (Julian et al. 2011). Such an approach is undertaken by following the scientific method where a hypothesis is proposed, and if this hypothesis cannot be disproven then it is confirmed (Neufeld & Scheck, 2010). This is a forward-thinking approach where the impact occurs in increments. In comparison, a criminal lawyer will establish the facts by assessing and questioning the evidence available to find discrepancies (Edmond, 2011; Cashman & Henning, 2012). This approach is undertaken by reviewing past cases to set a case precedent and is a more backward-thinking method compared to science (Cloatre & Pickersgill, 2014).

These different infrastructures and different ways of creating, dealing with and applying knowledge is where science and law can often be in conflict (Jasanoff, 1995). For instance, law is quick-paced where the answers need to be given within the duration of the investigation. Whereas, progress in science is slower and the 'truth' can change depending on scientific advancement (Neufeld & Scheck, 2010). Therefore, it is important for both lawyers and forensic scientists to understand the scientific and legal spheres to ensure that these differences are understood (Cassella & McCartney, 2011). This lack of understanding is hindering both forensic scientists and lawyers in fulfilling their responsibilities to the court (Howes, 2015; Edmond, 2013; Ligertwood & Edmond, 2012). For instance, it has been shown that without increasing their scientific understanding, lawyers are unable to place evidence under sufficient scrutiny (Edmond et al. 2014; Cashman & Henning, 2012; Ledward, 2004). Additionally, without a better legal understanding, forensic scientists are unable to fully contribute to a case as they are often tasked to answer legal questions (Cassella et al. 2011).

Thus, this chapter will provide key recommendations to the forensic science community to improve communication between lawyers, forensic scientists and policymakers on casework and research by reviewing the previous two experimental chapters and the published literature. This will be accomplished by reviewing the difficulties of implementing an evidence base by drawing on the evidence-based medicine and policing literature. Next, on the research level, this chapter will explore the need to incentivise forensic scientists and lawyers to collaborate on experimental studies by demonstrating their role and the benefits of such studies. Lastly, collaboration will benefit casework by implementing different approaches of communicating results in casework, and provide opportunities to seek further clarification.

5.2 Implementing an evidence base in forensic science

The need to undertake empirical research to implement an evidence in forensic science has been extensively advocated (Gherghel et al. 2016; Koehler & Meixner, 2016; McElhone et al. 2016; Morgan et al. 2009). This has been met with different responses from the forensic science community which has inhibited any major changes thus far (Edmond, 2003, 2010; House of Commons, 2013; Koehler & Meixner, 2016). However, there seems to be an idea that by implementing an evidence base that professional experience or opinion will be voided, and that unless science can underpin interpretation that findings should be inadmissible (Edmond, 2003; Koehler & Meixner, 2016). In evidence-based medicine, the concept of evidence-based decision-making is about ensuring that decisions are made based on the most up-to-date, solid, reliable, and scientific evidence (Djulbegovic, 2017). Some difficulties with the definition of EBM is that people think it advocates 'cook-book' medicine by treating patients according to a formula or an algorithm. However, EBM is only one aspect of clinical decision-making (Haynes, 2002). This does not mean that experience does not play a role in interpretation or that the specific needs of a patient should be overlooked. Additionally, policing has met resistance to evidence-based policing (EBP) as a lot of police officers believed that all police should develop a skilled intuition as the base of decision-making and this can only be obtained through professional experience (Sherman, 2015). Similarly, in forensic science, practitioners have argued that their professional experience is sufficient to interpret evidence (Koehler & Meixner, 2016). However, as can be learnt from EBM and EBP, it is important to consider the experience of practitioners to account for the variables unique to a case when interpreting evidence. This was shown in chapter 4 where 45% of criminal lawyers agreed that experimental studies can help provide context but that experience is invaluable to interpreting evidence. By considering these different aspects to form a conclusion, it allows for both the tacit and explicit knowledge to be incorporated (Doak, 2008). Thus, robust interpretation should be based on empirical studies and professional experience.

Further, when looking into evidence-based policing, it can be seen that an evidence-based approach is not simply about generating more or better research on police organisations and their practices, it is also concerned with how research is understood, translated, and implemented in everyday policing practice (Lum, 2009; Lum & Koper, 2014). This is important to consider in forensic science because, with the abundance of research papers released, it is difficult to focus on 'valid' research or the research with the 'best' findings (Haynes, 2002). Additionally, it is imperative to establish the most forensically applicable studies and how to apply such research. For instance, it is difficult to rate research when the results of studies that are similar methodologically frequently disagree with one another (Haynes, 2002). This also means acknowledging that only a tiny fraction of the forensic science articles provide new knowledge that is both adequately tested and important enough for practitioners to depend upon and apply (Edmond et al. 2016). As such, there is a need to implement a system to objectively identify and summarise evidence as it accumulates to allow users to find the best current evidence. This means there needs to be adequate resources and incentives to progress forensic science where it is at the point where an evidence base can be successfully implemented (Harrison, 1998). Thus, to implement an evidence base in forensic science, there is a need to review the current published literature and determine a way to systematically review such research (Harrison, 1998; Djulbegovic, 2017).

Reviewing the forensic science published literature highlights that forensic scientists do not tend to use research to underpin interpretation (Koehler & Meixner, 2016; Ligertwood & Edmond, 2012). This was supported by chapter 4 which demonstrated that only 44% of forensic scientists agreed that the published literature had frequently assisted with interpreting evidence. Further, 72% agree that the published literature allows forensic experts to provide more robust interpretation; this varied depending on employment where barristers agreed more and court experience (those with more court experience). These results emphasise that most forensic scientists and criminal lawyers do not find the published literature helpful to underpin interpretation. As such, there is a need to identify the barriers in place that are hindering the use of the published literature to support interpretation.

Two possible barriers that have been touched on are the abundance of literature available and the forensic relevance of the literature. For instance, only 21% criminal lawyers said they could find the information they needed. This has been highlighted in EBM where Metcalfe (2001) identified that because the literature is not in one place, it is difficult to find the required information. Additionally, reviewing the forensic science literature has highlighted concerns that experimental studies are forensically irrelevant as such studies focus on controlled settings

(House of Commons, 2005; Edmond, 2010; Koehler & Meixner, 2016). More specifically, the results from chapter 4 found that 47% of forensic scientists agree that the published literature was forensically relevant depending on their work and court experience (where those with more experience tend to find it less relevant). This is because, in forensic science, there are always unknowns in a criminal investigation that cannot be accounted for. A similar concern was highlighted in medicine where EBM has an image as appearing disease-oriented instead of patient-oriented (Bensing, 2000). This can be seen when looking at the research on randomised clinical trials. The patients that enrol on such trial must fit an inclusionary criterion to be allowed on them. This means that the evidence acquired from such trials will provide the doctors with scientific research but not on the variables that are unique to a patient. Taking this example, the importance of both establishing the general behaviour of a disease or an item of evidence is highlighted, but also the need to consider the external variables such as the patients' medical history or, in a forensic context, the variables unique to the investigation.

This was further highlighted as 40% of forensic scientists agreed that the published literature provides a good foundation to forensic science. This result varied depending on whether the forensic scientists was based in the UK or not and work experience. Thus, those with more work experience were less likely to agree. Whilst, 69% of criminal lawyers access the published literature to increase forensic understanding. This result varied depending on education (where masters were more likely to agree) and employment (where barristers use the literature more). Thus, to efficiently implement an evidence base, there is a need to consider the role of experimental studies in forensic science.

5.3 Role of Experimental Studies/communicating research

The first step towards implementing an evidence base in forensic science is to clearly establish the role of experimental studies to underpin interpretation. The previous section highlights the importance of considering the most up to date research but to also consider the variables unique to the case. To consider both these aspects when empirically establishing the behaviour of evidence, there is a need to perform a primary level and a secondary level of experimentation (see chapter 2, section 2.2). The primary level of experimentation is important as it gains insight into the behaviour of forensic evidence under different conditions. This was demonstrated in chapter 4, which tend to find that 75% of forensic scientists agree that experimental studies can help understand the transfer and persistence of evidence. Even though this result varied depending on court experience, where those with less court experience were more likely to agree, it does demonstrate that this type of research could possibly establish a primary level of experimentation.

Further, to demonstrate the utility of experimental studies to better understand the behaviour of forensic evidence, chapter 3 investigated the transfer, persistence and analysis of GSR. Overall, this chapter demonstrated the complexity of forensic interpretation and the need to gain insight into how an item of evidence behaves under different circumstances. Specifically, chapter 3 demonstrated the difficulty of interpreting the meaning behind the presence of a GSR particulate on clothing of a bystander. This was highlighted in experiment 1a where the distribution of GSR on the clothing of the three bystanders standing around the shooter did not display any observed pattern when comparing the consecutive runs on the same day or the three different days. Additionally, this was demonstrated in experiment 1b where the bystander (witness 2) standing behind the shooter did appear to have a significant difference between the particulate count and the area of the clothing. Additionally, it was shown that in run 3 consistently had more GSR than runs 1 and 2. Further, there was no significant difference between the different days. These results demonstrated the possibility that GSR remains in the atmosphere. However, due to the variability and the lack of reproducibility, the behaviour of GSR appears to be currently too complex to establish a general rule of behaviour. This was further emphasised when looking at the GSR distribution of a bystander standing to the right of the shooter (witness 3). The results from witness 3 showed no obvious visual pattern when looking at the individual body parts. When looking at the particulate count in January, there was GSR in run 3 than runs 1 and 2. However, there was no difference between the runs in April and July. Lastly, when comparing witness 3 to witness 2, it was possible to deduce that witness 3 always retained more GSR particles than witness 2. This could because witness 2 was standing behind the shooter which partially blocked the deposition of GSR onto the bystander. This possibly suggests a pattern to the standing arrangement of the bystanders compared to the shooter but extensive further work would be needed before any firm conclusions could be drawn.

Additionally, chapter 3 demonstrated the difficulty of establishing a general retention time of GSR on clothing as each witness retained GSR for a different amount of time. For instance, witness 1 retained GSR on the hoodie for 2 hours and on the jeans for 6 hours. Similarly, witness 3 retained GSR on the hoodie for 4 hours and on the jeans for 6 hours. However, witness 2 retained GSR on both items of clothing for 12 hours. This demonstrates the variability of GSR retention. Thus, the transfer and persistence of GSR is variable and it is difficult to not only interpret the meaning of detecting a GSR particulate at a particular location, and it also demonstrates the difficulty of placing any weight on that interpretation.

This is especially true because the literature has highlighted the effect that different variables have on GSR retention and that it is difficulty to establish any general rule of behaviour (French & Morgan, 2015; French et al. 2014; Aliste & Chávez, 2016; Gerard et al. 2011). Further, establishing a timeframe is further complicated as it is currently not possible to quantify the amount of GSR at t=0. Thus, to empirically and robustly establish a timeframe, there is a need to have known amounts to allow the rate of loss of GSR particles to be properly established.

This complication was further highlighted when investigating the use of the crime-Lites 82s and the p-XRF to visualise and characterise GSR. The results show that detection was possible and that this combined approach could possibly reduce the number of samples taken and incentivise sampling. However, these results also identified that without obtaining known amount of GSR, it is currently not possible to empirically establish a suitable screening tool for the SEM/EDX as it is not possible to gain empirical, reproducible data on detection limits and accuracy of the technique. These findings underpin the assertion that there is a need, and value in, performing empirical, reproducible studies to provide robust interpretation to court. This is especially important for more complex forms of evidence such as GSR to establish what information can be deduced and what information cannot. For instance, a practitioner could demonstrate x amount of studies to explain their reasoning similarly to medicine (National Research Council, 2009; Djulbegovic, 2017). This allows the jury to accurately assess findings based on these studies.

Overall, this demonstrates that establishing a primary level of experimentation can be beneficial to establishing general rules of behaviour. However, to apply such studies to establishing a secondary level of experimentation, there is also a need to improve on the standard of research being undertaken. For instance, chapter 4 found that only 48% of forensic scientists feel empirical studies make it easier to demonstrate the validity of interpretation. This result varied depending on those based in the UK or not, employment, and work experience. This means that academics and those with less work experience are more likely to agree that the published literature can support interpretation. Thus, if additional research is to be undertaken, there is first a need to determine a way to improve on forensic science research so that practitioners will use it to underpin interpretation.

To improve on forensic science research, there is a need to communicate and collaborate between forensic academics, practitioners and criminal lawyers (Silverman, 2011; Chief Scientific Officer, 2015). One hindrance to communication is that research usually focuses on practitioners and lawyers as research consumers instead of conductors of research, particularly when looking into the collaborations between practitioners and academics (Guillaume et al. 2012; Sidebottom & Tilley, 2010). This is especially important to consider in forensic science because chapter 4 found that 44% of forensic scientists tend to agree that academics lack the practical experience to understand forensic realistic research. This varied depending on court experience, where those with more court experience were more likely to agree. However, the EBP literature highlights similar problems in policing where (1) research-practitioners' collaborations are desirable, (2) documented examples of effective collaborations are limited, (3) more could be done to promote and facilitate such collaborations (Bradley & Nixon, 2009; Cordner & White, 2010). To demonstrate the benefit of such collaboration, Guillaume et al. (2012) presented a case-study in policing on a successful collaboration between academics and practitioners. They concluded that practitioners found working with academics added substantially to their knowledge. The academics provided interest and support as well as academic rigor. Having an academic on the research team meant ideas would be tested and advised throughout the project. Additionally, academics found collaborating with practitioners increased the practical applications of the research. Further, research in forensic science where practitioners and academics have collaborated have shown to have beneficial practical results (Earwaker et al. 2015). When looking into the collaborative efforts in forensic science, the results from chapter 4 showed that 82% of forensic scientists do tend to perform or collaborate on experimental studies. This result varied depending on age, education, employment, and work experience. That is, academics and those with less work experience tend to be more willing to collaborate on such studies. Additionally, the results from chapter 4 found that 90% of forensic scientists tend to agreed that there is a need to increase collaboration between academics and practitioners. This result varied on employment and between forensic scientists based in the UK or not. That is, forensic scientists in the UK and practitioners are less likely to agree for the need to collaborate. There are places where there is greater synergy between the different actors. For instance, in the Netherlands, the NFI (Netherlands forensic institute) have practitioners and academics side by side and visiting posts at allied universities for those within the NFI environment (Netherlands Forensic Institute, 2017). Additionally, in Australia, they have been promoting the collaboration between practitioners and academia in their strategic strategy (ANZPAA, 2015). Thus far, such collaborations have been occurring more frequently. For instance, the Victoria Police who work with 3rd year undergraduates and postgraduate students on a range of projects (Victoria Police, 2017). Thus, these results and examples emphasise the need to improve on collaboration and potentially undertake studies to empirically demonstrate the benefits of a collaborative approach between forensic practitioners and academics.

Further, improved communication with criminal lawyers on forensic science research is also imperative. This is especially important because if lawyers are going to put forensic evidence under sufficient scrutiny then lawyers need to understand the strength and weaknesses of empirically studies used in court to support interpretation (National Research Council, 2009; Gatowski et al. 2001; Ledward, 2004). More specifically, chapter 4 found that 45% of criminal lawyers said they tend to feel more confident raising doubts on experimental studies than professional experience. This varied depending on education where those with a Master were less likely to agree. That is, masters who tend to have more experience accessing published literature are less likely to agree. This result demonstrates that criminal lawyers do not appear to understand the role of experimental studies because they would rather raise doubts on quantifiable and empirical research than professional experience (which cannot be quantified). Additionally, the results from chapter 4 showed that 62% of criminal lawyers agreed that increase collaboration between forensic scientists and lawyers is needed. Accordingly, by increasing collaboration between lawyers and forensic scientists will allow lawyers to gain insight into the experimental studies and provide them with the opportunity to assist and ask questions to improve their forensic understanding.

Overall, it has been shown that, without effective and clear communication, the relevant research cannot be undertaken. That is, collaborating on case-based studies ensures that the appropriate questions are being addressed in the context of the case (Saks & Faigman, 2008; National Research Council, 2009; McCartney & Cassella, 2013). This allows the criminal lawyer to make clear the questions that need to be addressed during the study, whilst the forensic scientists can ensure that the study is forensically realistic and communicate the meaning and context behind the findings. This would ensure that forensically relevant research is undertaken in collaboration between criminal lawyers, forensic practitioner and academics. This goes some way to establishing an evidence base in forensic science that can be drawn upon to demonstrate the robustness of interpretation in court.

5.4 Communication between policymakers, forensic scientists and lawyers

Communication between policymakers, forensic scientists and lawyers is essential to ensure that all parties are aware of the concerns raised by the NAS report and the subsequent reports that have followed, such as the PCAST and the Forensic Science Regulator reports (National Research Council, 2009; Executive Office of the President President's Council of Advisors on Science and Technology, 2016; Forensic Science Regulator, 2016). This is important because, without fully understanding the concerns that were raised by the NAS report and subsequent reports, lawyers and forensic scientists are not fully aware of the concerns raised of the lack of scientific underpinning in forensic science This means that these stakeholders are potentially over- or undervaluing the robustness of forensic evidence (Cashman & Henning, 2012; Edmond, 2001; Ledward, 2004). This is especially true because it is the responsibility of forensic scientists and lawyers to convey the findings to the court, and ensure that the jury are aware of the strength and limitations of these findings(Howes & Kemp, 2017). Moreover, the lack of scientific underpinning needs to be addressed as it emphasises the weakness of forensic evidence, which is causing the continued use of particular types of forensic disciplines to be questioned (Executive Office of the President President's Council of Advisors on Science and Technology, 2016; Forensic Science Regulator, 2016; Chief Scientific Advisor, 2015). Thus, lawyers and forensic scientists need to be aware of the latest research and development in forensic science to ensure that the most up-to-date techniques are being used, and that the most recent research is being considered.

However, to develop the general communication between forensic scientists, lawyers and policymakers, there is a need to review the current level of communication between these different stakeholders. For instance, the results from chapter 4 highlighted that only 44% of forensic scientists and 34% of criminal lawyers would rate their current level of communication as high. Additionally, 97% of forensic scientists and 90% of criminal lawyers agree that there is a need to increase communication. Thus, there is a need to identify the barriers between these different stakeholders to develop a way of opening the lines of communication between them. Improving on the communication between these stakeholders, there could incentivise lawyers and forensic scientists to participate in these experimental studies by demonstrating their role in the study or the utility of such studies.

One barrier for good and efficient communication that has been identified is the lack of access to relevant information and the use of clear language (Silverman, 2011; Howes et al. 2014; Edmond, 2013). In practice, that means that forensic scientists need to learn to communicate with their scientist peers and with non-scientists (Howes & Kemp, 2017; Bubela et al. 2009). Research into the communication in the medical field has shown that there is a similar obstacle with the lack of comprehensible and useable written and spoken language (Calderón & Beltrán, 2004). This was highlighted in forensic science as well where there is a need to speak a common language to ensure that findings are being understood across science/law borders (House of Commons, 2005; Howes et al. 2014; Taroni et al. 2013). This is especially important because the scientific language is a specialised language with grammatical features that makes it differ from language used in the general public (Howes, 2015). For instance, there are differing languages between policy reports, laboratory reports, court reports and scientific journals. Thus, there is a need to consider who is going to read a particular report because one method of communication might work between forensic scientists, that does not work between forensic scientists and policymakers, because they have different aims and requirements of knowledge (Coiera, 2006). This was shown by Howes (2017) which looked into the perception of police officers on the way forensic science is reported in Australia. This study highlighted that, for most cases, this one-way form of communication is sufficient but that for more complex cases a two-way method of communication is needed.

To facilitate communication, the medical field have found that face-to-face preliminary consultations are essential to providing a solid foundation of communication between general practitioners (GPs) and specialists. In forensic science, there is limited interaction between forensic scientists and lawyers. This is because forensic scientists formally communicate their results to police officers and lawyers in the form of written reports. Additionally, there is limited interaction between scientists and lawyers in a pre-trial context (Howes et al. 2013). For instance, Howes et al. (2014) has highlighted that pre-trial conferences between forensic scientists and lawyers tend to be brief and underused. Whereas, having an initial consultation could ensure that everyone has a clear introduction and understanding of the scientific results from the beginning.

Additionally, the medical field have implemented template reports to allow information to flow freely between experts, GPs, nurses and patients when discharged from the hospital and needing continued health services (Radius et al. 2006). A similar approach has been undertaken by the engineering and physical science research council (EPSRC) where they provide a one-page summary report on key findings on different scientific subject (EPSRC, 2016). This report is written using 'policy' language, instead of scientific language, to allow for a clear overview of the report, and for the key findings and recommendations to be expressed. This was also recommended by the NAS report who suggested developing model report templates for each forensic discipline and development of standard terminology (National Research Council, 2009). This template would standardise the way experts present their findings to lawyers and the courts. For instance, Edmond et al. (2016) suggested that reports and testimony should be transparent to allow for non-scientists to review and understand how the evidence was collected, processed and analysed, how particular conclusions were reached and provides insight into the limitations and uncertainty associated with the findings. Additionally, Howes et al. (2015) suggested that the format of the report should state the context of purpose, present sufficient information, present key findings, make inferences and assumptions explicit, define unusual or scientific terms in text, and refer to the items compared using concrete terms. This would set a clear flow and layout from the beginning of the report. By standardising the presentation of evidence, it will increase clarity for the courts on the robustness and meaning of the scientific findings. Additionally, it will assist forensic scientists to either avoid presenting opinion evidence alongside these findings or clarify the aspects that are opinion-based (Koehler & Meixner, 2016; Edmond, 2013).

Improving on the clarity of the findings may assist lawyers with focusing on the scientific validity of the findings. For instance, Edmond et al. (2014) urge lawyers to focus their questions on the relevance of the findings, the validation of techniques, limitations and errors that should be considered, personal proficiency, expressions of opinion, verification, and any potential cognitive bias and contextual effects that may have arisen. However, it is difficult to question and find discrepancies in scientific findings if lawyers do not have any scientific training (National Research Council, 2009; McCartney & Cassella, 2013). Additionally, providing a standardised format does not provide guidance on the legal questions that need addressing. Thus, there is a need to improve not just communication but also the legal and scientific understanding of forensic scientists and lawyers.

5.5 Conclusions

This chapter has outlined two areas of communication that could be improved: (1) general communication between forensic scientists, criminal lawyers and policymakers on casework, and (2) communication between forensic academic, practitioners and criminal lawyers on forensic science research. Improving communication in these areas will ensure that criminal lawyers and forensic scientists are better equipped to collaborate on casework and research and increase the use of evidence-based interpretations.

Specifically, to implement an evidence base in forensic science, it is important to understand that:

1) There is a need to implement an evidence base in forensic science. However, implementing such a base does not mean that professional experience should be excluded. Evidence-based decision-making is one aspect of interpretation to assist with supporting the reasoning of the expert. However, there is also value in considering professional experience to assess the variables unique to a case.
2) There is an abundance of literature that is published every year making it difficult to determine the ‘good’ and ‘valid research. Additionally, this makes it more difficult to determine which study is most relevant to supporting the findings in a particular case. Thus, there is a need to determine a way to systematically review the literature.

3) Reviewing the published literature identified the need to need to identify the barriers hindering the use of the published literature to support interpretation. This was shown because only 44% of forensic scientists tend to agree that they frequently use the literature to assist with interpretation. Additionally, 69% of criminal lawyers tend to use the published literature to increase their forensic understanding but only 21% found the information required. This was further demonstrated as 47% of forensic scientists agreed that the literature was forensically relevant.

Secondly, there is a need to understand the role of experimental studies to establish an evidence base, particularly:

1) There is a need to perform studies on the primary level of experimentation to understand how evidence behaves under different conditions. This was shown as chapter 4 found that 75% of forensic scientists tend to agree that experimental studies can help understand the transfer and persistence.
2) GSR is a prime example of the need and value in undertaking empirical research. This was demonstrated in chapter 3 which highlighted the complexity of placing meaning behind finding a GSR particulate on a particular location. It specifically showed that there no clear pattern to the way GSR distributes on the clothing of the three bystanders. Additionally, it demonstrated that the rate of persistence on clothing varies as the retention time of three bystanders varied for each of them, as did the persistence of GSR on clothing after washing where detection was possible but difficult. Further, chapter 3 demonstrated that establishing a suitable screening tool based on empirical evidence is further complicated as it is not possible to get known amounts of GSR. Thus, these chapters demonstrated that there is a need to perform research on the transfer, persistence and analysis of evidence to increase understanding into the way evidence behaves. This will ensure that the most robust form of interpretation is being presented in court based on empirical, reproducible data.
3) However, there is also a need to perform secondary level of experimentation as there are variables unique to a case that cannot be account for in research. To establish this secondary level, there is a need to improve on the standard of research being undertaken. For instance, chapter 4 found that only 48% of forensic scientists tend to feel empirical studies make it easier to demonstrate the validity of interpretation.
4) To improve on forensic research, there is a need for clear and effective communication between lawyers and forensic scientists. This allows the criminal lawyer to make clear the questions that need to be addressed during the study, whilst the forensic scientists

can ensure that the study is forensically realistic and communicate the meaning and context behind the findings.

Lastly, there is a need to improve the general communication between forensic scientists, criminal lawyers and policymakers, particularly:

1) There is a need to ensure that all parties are aware of the concerns raised by the NAS report on the lack of scientific underpinning and the reports that have followed since. This will enable policymakers, lawyers and forensic scientists to communicate and determine the best way forward.
2) There is a need to develop communications between criminal lawyers and forensic scientists. The results showed that only 44% of forensic scientists and 34% of criminal lawyers would rate their communication as high. Additionally, 97% of forensic scientists and 90% of criminal lawyers agree that there is a need to increase communication. Thus, there is a need to find a way to open these lines of communication and incentivise collaboration. The literature has identified possible solutions to opening these lines of communication by implementing face to face meetings and template reports to ensure the clear use of languages and access to information.

Overall, these recommendations underpin the assertion that improved communication in these different areas can go some way to start addressing the lack of scientific underpinning in forensic science and the need to implement an evidence base.

Chapter 6: Conclusions

6.1 Summary of findings

The overall aim of this thesis was to explore the complexity of implementing an evidence base in forensic science. This was approached by exploring two areas: (1) the need to perform experimental studies into more complex forms of evidence and (2) the receptivity of forensic scientists and criminal lawyers to the use of evidence-based interpretation.

The use of experimental studies was explored because there have been concerns that these experimental studies cannot assist with interpretation as these studies focus on a primary level of experimentation. That is, these studies do not consider variables unique to the case and thus cannot be applied in practical settings. Thus, improving communication and collaboration will subsequently improve on the standard of research being undertaken and ensure such research has more practical applications. To do this, there is a need to open the lines of communications between these different stakeholders to ensure that (1) criminal lawyers clearly understand the findings to place it under sufficient scrutiny, (2) practitioners can use research to assist with forensic interpretation and (3) academics get the support they need to improve on the forensic relevance of their research design. However, to accomplish this, these stakeholders need to understand the current research landscape of forensic science and the role of experimental studies to establish an evidence base.

Further, the receptivity of criminal lawyers and forensic scientists on the use of evidence-based interpretation was investigated. This was investigated because in the last decade there have been multiple policy reports that have highlighted the lack of scientific underpinning in forensic science and the need to perform empirical reproducible studies (Executive Office of the President President's Council of Advisors on Science and Technology, 2016; Home Office, 2016; Forensic Science Regulator, 2016; National Research Council, 2009). However, this suggestion has caused a contentious debate in the forensic science community where some have argued that professional experience is sufficient for accurate interpretation (Koehler & Meixner, 2016) and others have argued that interpretation should be based solely on experimental studies to demonstrate empirical, reproducible data (Ligertwood & Edmond, 2012). However, a third argument has said that robust interpretation is based on a combination of professional experience and empirical studies (Mnookin et al. 2011). Thus, there is a need for policymakers, lawyers and forensic scientists to improve on communication to determine the best approach to providing robust interpretation.

Therefore, this thesis sought to address the following questions:

1) What is the impact that additional research can have on forensic interpretation and can it account for the more complex forms of evidence?
2) How much consideration the views and experience of research evidence as a foundation on which to make forensic decisions is given by forensic scientists and lawyers?
3) In the light of the findings of questions 1 and 2, what are the key recommendations to the forensic science community to improve communication between forensic scientists and lawyers on casework and on research?

The individual chapters of the thesis have highlighted that there is a need to improve communication between the different actors in forensic science casework and research.

6.1.1 The impact that additional research can have on forensic interpretation

Chapter 3 demonstrated the complexity of interpreting GSR under different conditions. This was highlighted in experiment 1 where the variability of GSR distribution was demonstrated. For instance, experiment 1a did not display any observed patterns when comparing three consecutive runs on the same day or on three different days. This was also demonstrated in experiment 1b where there was no clear pattern between witnesses 2 and 3 and the areas of where GSR was retained. However, it did find that witness 3 tend to have more GSR than witness 2 which could provide an indication of the standing arrangement but extensive further work would be needed before any firm conclusions can be drawn. Thus, due to the variability and the lack of reproducibility, the behaviour of GSR appears to be currently too complex to establish a general rule of behaviour.

Additionally, chapter 3 demonstrated the difficulty of establishing a general retention time of GSR on clothing as each witness retained GSR for a different amount of time ranging from 2 to 12 hours. For instance, witness 1 retained GSR on the hoodie for 2 hours and on the jeans for 6 hours. Similarly, witness 3 retained GSR on the hoodie for 4 hours and on the jeans for 6 hours. However, witness 2 retained GSR on both items of clothing for 12 hours. This demonstrates the variability of GSR retention and the difficulty of establishing the meaning of detecting a GSR particulate at a particular location. Further, establishing a timeframe is further complicated as it is currently not possible to quantify the amount of GSR at t=0. Thus, to empirically and robustly establish a timeframe, there is a need to have known amounts to allow the rate of loss of GSR particles to be properly established.

This complication was further highlighted when investigating the use of the crime-Lites 82s and the p-XRF to visualise and characterise GSR. The results show that detection was possible and that this combined approach could possibly reduce the number of samples taken and incentivise sampling. However, these results also identified that without obtaining known amount of GSR, it is currently not possible to empirically establish a suitable screening tool for the SEM/EDX as it is not possible to gain empirical, reproducible data on detection limits and accuracy of the technique. These findings underpin the assertion that there is a need, and value in, performing empirical, reproducible studies to provide robust interpretation to court. This is especially important for more complex forms of evidence such as GSR to establish what information can be deduced and what information cannot. For instance, a practitioner could demonstrate a range of studies to explain their reasoning similarly to medicine (National Research Council, 2009; Djulbegovic, 2017). Thus, this chapter demonstrates the complexity but also the value of undertaking such studies. By gaining insight into this complexity, it still provides insight on what information can or cannot robustly be interpreted from GSR evidence. However, due to this complexity, it is imperative to clearly communicate these findings to allow them to be accurately assessed by the jury.

6.1.2 The views and experience of forensic scientists and lawyers on research evidence as a foundation on which to make forensic decisions

The results presented in chapter 4 showed that only 44% of forensic scientists tend to agree that the literature can frequently assist with interpreting evidence; this result varied on age and work experience where the more experienced forensic scientist was less likely to agree. Additionally, only 40% of forensic scientists tend to agree that the published literature provides a good introduction to forensic science. However, 69% of criminal lawyers tend to access the published literature to increase forensic understanding. Thus, there is a need to identify the barriers that are inhibiting the use of the published literature. Two possible barriers that were identified was that the literature is not found in one place and the forensic relevance of the literature. For instance, only 21% criminal lawyers could find the information required and 47% of forensic scientists agree that the published literature was forensically relevant (where those with more experience tend to find it less relevant).

When exploring the use of case-based studies, the results from chapter 4 showed that 82% of forensic scientists do tend perform their own experimental studies. This result varied where academics and those with less work experience are more likely to perform such studies. Even though, only 48% of forensic scientists tend to find that empirical studies make it easier to demonstrate the validity of interpretation. This result varied depending where academics and those with less work experience are more likely to agree that empirical studies can support interpretation. Additionally, 75% of forensic scientists agree that experimental studies can help understand the transfer and persistence of evidence. Thus, if additional research is to be undertaken, there is a first a need to demonstrate the role of experimental studies to incentivise its use. This is especially important because 45% of criminal lawyers said they more confident raising doubts on experimental studies than professional experience. This varied depending on education where those with a Master were less likely to agree.

When reviewing the communication and collaboration between forensic practitioners and academics, the results from chapter 4 highlighted that 97% of forensic scientists and 90% of criminal lawyers agree that there is a need to increase communication. However, only 44% of forensic scientists and 34% of criminal lawyers would rate their current level of communication as high. Therefore, there is a need to gain further insight into the barriers between these different stakeholders to develop a way of opening the lines of communication between them. Additionally, there is a need to incentivise lawyers and forensic scientists to participate in these experimental studies.

6.1.3 The key recommendations to the forensic science community to improve communication between forensic scientists and lawyers on casework and on research

Whilst reviewing these two experimental chapters and the published literature, chapter 5 identified key recommendations to improve the communication between forensic scientists and criminal lawyers on casework and research by focusing on the EBM and EBP literature. Examples of recommendations for casework are pre-trial conferences between forensic scientists and lawyers and implementation of template reports to increase clarity. Further, it was identified that, to improve the standard of forensic science research and implementing an evidence, there is a need to improve collaboration between academics and practitioners. Additionally, it was emphasised that the receptivity of EBM and EBP in the medical and policing community has also been met with apprehension. This apprehension is because of a misunderstanding where evidence-based decision-making is the only aspect to consider when interpreting evidence. However, evidence-based decision-making is only one aspect of interpreting evidence to assist and support findings to demonstrate the experts' reasoning and the weight of the findings. It is still important to consider professional experience to account for the variables unique to a case.

Thus, overall this thesis established that the key to progressing such a stage of evidence-based interpretation is by improving communication and collaboration between forensic academics, practitioners and criminal lawyers.

6.2 Overall conclusions

Overall, this thesis concludes that there is a need to improve on communication and collaboration between forensic scientists and criminal lawyers on research and casework. Improving communication in research between forensic practitioners, academics and criminal lawyers is important because, as illustrated in chapter 3, understanding the behaviour of evidence such as GSR can be difficult due to the variability in its deposition and persistence. This complexity of establishing a general rule of behaviour is further exacerbated by the difficulty of obtaining GSR with known quantities. Thus, it is important for forensic scientists and lawyers to understand these complications in undertaking research on GSR and hence understand the information that can or cannot be deduced from the evidence available. Additionally, improving communication on casework will highlight the gaps of knowledge in forensic science and the role of experimental studies. For instance, chapter 4 demonstrated that most forensic scientists do not tend to frequently use the published literature to support interpretation. Further, the results showed that most forensic scientists do tend to undertake their own empirical studies, but there is little collaboration and communication between forensic academics, practitioners and criminal lawyers on these studies to increase the research impact. Therefore, there is need to identify the barriers that are inhibiting communication and develop a way of opening the lines of communication between them. This is already further along in development in certain places such as in Australia and the Netherlands. Suggestions to opening these lines of communication in the UK vary from initial consultations, additional face-to-face meeting and standardising of forensic science reports. By implementing such measures, it might be possible to improve communication and collaboration which subsequently could improve forensic science research and casework.

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