THE IMPORTANCE OF SCIENTIFIC AND TECHNICAL INNOVATION IN THE POLICE INVESTIGATION OF GUN CRIME

JENNIFER THOMAS

A Thesis submitted to the University of Huddersfield in partial fulfilment of the requirements for the degree of Doctor of Philosophy

The University of Huddersfield

September 2011

Copyright Statement

Acknowledgments

Thank you to everyone at Forensic Pathways for the support over the past three years. Thanks also to Alex, Liam and Rachel at Huddersfield.

This research would not have been possible without the support and co-operation and collaboration shown by the two companies that participated. Thank you to everyone at these two companies.

Thank you to all members of the European Network of Forensic Science Institutes Firearms Working Group (ENFSI FWG) who generously provided support, advice and ammunition.

Thank you also to everyone involved with the Odyssey Project.

Contents

Word Count (excluding Appendices): 78,768

List of Tables

List of Figures

Abstract

My original contribution to knowledge is the assessment of two ballistics analysis systems using the same bullets and cartridge cases to assess interoperability potential. The results are discussed in the context of policing issues representing a multidisciplinary approach to combating gun crime.

Microscopic comparison of bullets and cartridge cases allows inferences to be made that objects bear marks from the same weapon. Parts of this process have been automated. Digital images of objects are stored in a database and correlations undertaken to find potential matches. An expert will decide on the most probable match based upon a range of potential candidates.

All evidence should be utilised to the fullest extent, including data from ballistics systems. The success rate of the most widely used system has been quoted at between 50% and 95% suggesting that links to other crimes remain undiscovered. There are different ballistics systems available but research has only been conducted on one.

There is no interoperability between systems. Data cannot be shared between different systems. An essential pre-requisite to any work on interoperability, is an understanding of the different systems and the data produced. The research aims were to design a methodology to enable the assessment of systems and to produce ammunition that can be used repeatedly as required. The aim was to conduct an experiment with two of the currently available systems.

The results show variance between systems and their accuracy needs improvement. An error rate has been defined and applied to each system. The results suggest that complete interoperability of systems will only be possible with the full cooperation of the manufacturers. A limited form of interoperability focussing on data sharing may be possible. The results have implications for experts using the systems and suggest that a matching standard should be developed to make forensic ballistics analysis an objective discipline.

Chapter 1 - Introduction

1.1 - Introduction

Gun crime presents a major challenge to law enforcement and the consequential investigations often involve forensic science. This may be through the analysis of DNA and fingerprint evidence in addition to the analysis of bullets, cartridge cases and recovered firearms. Forensic ballistics involves the comparison of bullets and cartridge cases to ascertain if the same weapon was responsible for firing the objects in question. During gun manufacturing, a tool is used to machine lands and grooves into the barrels. This ensures a stable trajectory of the bullet when the weapon is fired. Wear inflicted on the machining tool every time a new barrel is cut, results in the rifling of each barrel being slightly different. During firing, these unique marks are transferred to the bullet. The same principle applies to the components of the weapon that make contact with the cartridge case. Unique impressions are transferred and can be used to infer matches between ballistics exhibits. Whilst these distinguishing characteristics can also be used to differentiate between individual weapons, they can also be used to determine the manufacturer of a particular weapon. One example is the rectangular firing pin impression typically found on cartridge cases fired from Glock pistols. These features are known as class characteristics as opposed to individual characteristics which identify a particular weapon.

Forensic ballistics is different to other areas of forensic science such as DNA testing and fingerprint analysis. DNA and fingerprints remain constant. Two DNA profiles from the same person taken years apart will be the same. Every time a gun is fired, the physical contact between the gun components and the ammunition results in wear. This changes the distinguishing marks. Two bullets or cartridge cases fired from the same gun will bear marks that are the same and depending on the number of times the weapon has been fired, will also bear marks that are different. This introduces complexity into the discipline which has resulted in an element of subjectivity when declaring matches between objects. Consequently, there are no standards in place to declare a match between bullets or cartridge cases. Expert testimony is based upon the skills and experience of the examiner rather than a statistical or probability based assessment of the evidence. The chances of a coincidental match between two questioned DNA profiles have been questioned, studied and published to a high degree of certainty. The same has not happened in the forensic ballistics discipline.

The physical examination of bullets and cartridge cases is conducted using an optical comparison microscope. Evidence based on this microscopic comparison is presented in court. Attempts have been made to automate parts of this process. Technology is now in place in many laboratories that allows a digital image of a bullet or cartridge case to be acquired, distinguishing marks extracted in the form of a digital signature and stored in a database. This allows comparisons to be carried out between many ballistics exhibits - a task that would be time consuming and arguably impossible for a human to undertake. These systems typically return a list of probable matches ranked in order of similarity. An expert will then have to examine the objects on the correlation list and make a decision as to the most probable match. The list may contain many objects. Different laboratories will examine the top five, top ten or top twenty.

There are different suppliers of these systems. However, there is no interoperability between different systems resulting in a situation where different countries using different systems cannot exchange data. This produces many difficulties for police investigating crimes involving firearms. It also results in a situation where a high level overview of the extent to which guns travel is difficult to obtain.

The systems do not return definitive matches, instead returning a list of similar objects. Previous research conducted on the most widely used system has found differing accuracy rates depending on many variables such as database size and ammunition type. Furthermore there has been no published research conducted on other systems available despite these systems beginning to gain prominence in the market. There has also been no published research examining potential interoperability between the systems currently available. This Thesis aims to address this through the design of a methodology specifically designed to enable the assessment of different systems using the same sample of bullets and cartridge cases. This will enable the extraction and examination of the resultant data to inform the debate on interoperable systems.

Whilst the experimental aspect of this Thesis concerns the automated systems that are used for the purposes of forensic ballistics analysis, the results and the application of these systems have been discussed in the context of wider policing issues representing a multidisciplinary approach. A problem facing police investigating gun crime is the lack of information that is sometimes available. This can be related to a single crime where victims and witnesses are reluctant to come forward. Equally, there can be a lack of information regarding the number of crimes being committed overall. Official statistics provide the number of recorded crimes but do not include unreported crimes. Consequently, it is difficult to quantify the true number of crimes involving firearms. This has led to alternative research methods being employed which have provided valuable information. These have included the assessment of medical information relating to gunshot related hospital admissions and interviews with offenders.

Whilst there are elements of forensic ballistics that are common between different jurisdictions, the nature and characteristics of gun crime and the individuals that commit these crimes can vary dramatically. Gun crime in countries outside the UK is not only different in terms of quantification, but also, in underlying differences in culture, history and legislation that affect the manifestation of gun crime. An example is the USA where legislation is different from the UK in that firearms are easier to acquire. A higher rate of gun crime than the UK is also observed. This contrasts greatly with Canada where compared to the USA, there is a smaller level of gun crime. Contrast this again with the Republic of Ireland which has a much higher number of murders committed with firearms than the UK despite the population differences. These contrasts demonstrate the fact that gun crime has many manifestations and consequently some interventions will be more appropriate in some situations than others. It is certainly true that a one size fits all approach cannot be applied.

Attempts have been made to address gun crime by understanding the factors that cause individuals to carry and use guns. Gun crime has been linked to gangs and associated criminality and consequently research has been undertaken to understand the problem and implement interventions. A notable example is the application of evidence based policing principles to the guns and gangs problem in Boston. Operation Ceasefire was put into place as a result of a high number of gun deaths in Boston in the 1980s and 1990s. Multiple agencies were involved and tackled both the supply of firearms and the individuals carrying them. Later research assessing the significance of the interventions concluded that Operation Ceasefire reduced the number of monthly youth homicides by 63% over the initial two years of implementation (Braga at el, 2001). In the UK, perhaps the best example of specialist police interventions is Operation Trident in London. This is a dedicated operational command unit tasked with investigating shootings primarily amongst the young, black community in London. Like Operation Ceasefire in Boston, Trident utilises a multi-agency approach to tackling the supply and demand of firearms (Robert and Innes, 2009).

A proposed solution to tackling gun crime is the implementation of a gun registration scheme. This would involve test firing all legally held weapons and entering the bullets and cartridge cases into a ballistics analysis system. Feasibility studies have been undertaken to assess the suitability of the technology to the task. The overall finding has been that the technology is not accurate enough to enable successful implementation of such a scheme. A prerequisite to such a scheme is a high level of accuracy. According to research conducted previously and also for this Thesis this is not present currently.

As previously described, gun crime presents law enforcement agencies with unique problems. Crimes involving firearms are often difficult to prevent, detect and understand. Strategic interventions targeting the supply and trafficking of firearms are also difficult to understand due to a lack of data available concerning the extent to which guns travel. The data gaps could be addressed through interoperable ballistics analysis systems allowing routine cross referencing of ballistics evidence between different countries. The major barrier to this is that current systems are not interoperable. Furthermore there has been no research conducted assessing the feasibility of interoperable systems. This Thesis aims to conduct a controlled experiment with two currently available systems to assess the data output in order to inform a debate on interoperable systems.

It has been suggested that new technology is required to bring greater accuracy to the discipline as well as significant efficiencies in terms of operating the technology and procurement costs. Suggestions are made throughout the Thesis of the forms that innovation in this field may take with particular reference to 3D surface metrology technology that is routinely used in other engineering disciplines. Such technology allows a detailed surface topography of an object to be captured and overcomes some of the flaws of using two dimensional technology to capture a three dimensional object. Throughout the Thesis, a further aim is to discuss the results in the context of some of the policing issues raised in the literature review. As such, the Thesis is organised as follows:

- **Chapter One** introduces some of the key issues and outlines the aims of the Thesis.
- **Chapter Two** consists of a review of the literature. The Thesis is multidisciplinary in nature and as such the literature review contains research conducted in both the criminology field and also the forensic ballistics field. In the forensic ballistics field, particular attention has been paid to research conducted on automated systems.
- **Chapter Three** presents the aims and objectives of the research. The gaps in the literature are identified and addressed.
- **Chapter Four** presents the methodology of the Thesis. This includes the background to the experimental research, the steps that were taken prior to commencing the experimental research and the experimental design.
- **Chapter Five** consists of the results and discussion.
- **Chapter Six** concludes the Thesis, presenting a discussion of the results in the context of wider policing issues, the conclusions and implications of the research and suggestions for future research.

Chapter 2 – Literature Review

2.1 Gun Crime - Reporting, Levels and Trends

2.1.1 - Gun Crime in the UK

This section explores gun crime from the perspective of the United Kingdom. Particular attention is paid to assessing the incidence of crimes involving firearms. Official statistics are discussed alongside studies that have utilised other methods such as historically assessing medical records from hospital admissions and interviewing offenders convicted of crimes involving firearms. The impact of these crimes is also discussed. The incidence of gun crime is put into the context of the UK's restrictive firearms legislation. The impact of this legislation is also discussed.

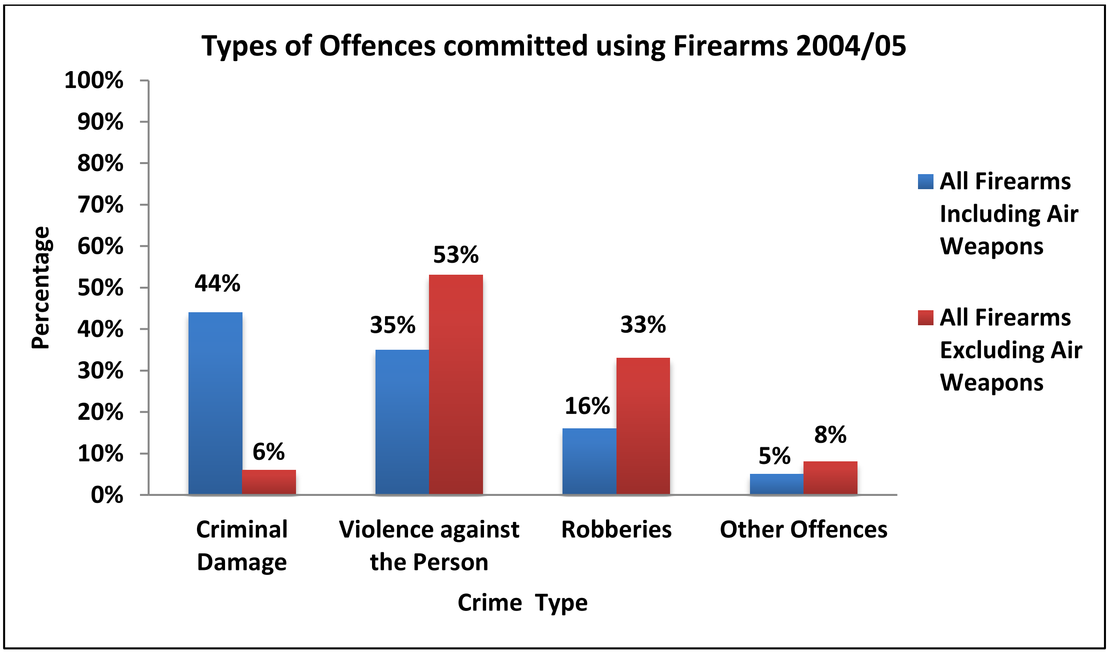
Crimes that involve firearms are frequently in the media both in the UK and abroad (BBC, 2008, BBC, 2009, BBC, 2010b,). The serious nature of these offences and the harm caused by them has resulted in extensive research being conducted investigating the causes and consequences of these offences and resultant interventions. These are discussed in detail in a later section of this Chapter. It is important to note that the term "gun crime" can have many different definitions depending on the context and the laws of any particular country. In England and Wales, the term "gun crime" means an offence that involves a firearm being discharged, used as a weapon (as a blunt instrument) against a person, or used to threaten a person. In this definition, air weapons are considered as firearms. (Smith et al, 2010). Other criminal events are also included in the definition of "gun crime" used in this Thesis, such as trafficking and the illegal distribution of firearms. In the United Kingdom the possession of firearms is strictly regulated resulting in the possession of a firearm being illegal in most circumstances (Warlow, 2007). In other countries such as the United States, firearms legislation is much more relaxed (Spritzer, 1998).

Quantifying the extent of gun crime can be problematic because some offences will be unreported (Squires, 2008). However, the Home Office releases crime figures annually which can be used to assess the number of reported crimes involving firearms. The latest figures available show that in 2008/09 gun crime accounted for only 0.3% of all recorded crimes in England and Wales (Smith et al, 2010). This percentage may seem low but the actual number of crimes represented is over 14,000. There were 432 fatal or serious gun crime injuries in 2008/09 according to Home Office statistics presented by Smith et al (2010). It is important to note that this figure includes incidents where air weapons were used and where a firearm was used as a blunt instrument or to threaten a person. Excluding air weapons, the number of firearms offences in 2008/09 was 8,208 (Smith et al, 2010). Although parts of this Thesis are concerned with the forensic analysis of bullet and cartridge cases fired by weapons, it is still of importance to consider incidents where firearms are not fired as these crimes can still generate valuable intelligence relevant to forensic ballistics such as descriptions of the weapon.

Compared to the previous year (2007/08), offences involving firearms (all types) fell by 18%, excluding air weapons, firearms offences fell by 17%. These statistics represent the fifth consecutive annual fall. Offences involving firearms are still substantial in number and important to quantify given the impact and harm caused by these types of offences (Smith et al, 2010). It is also important to note that a gun does not have to be fired or used as a weapon to cause harm. The threat posed by a firearm can be extremely distressing and used to enable a crime such as robbery. Smith (2003) examined a sample of over 2,000 personal robberies and found that 3% of all personal robberies involved the use of a firearm.

It is important to recognise that the term gun crime does not define a crime type. Crime types involving firearms are varied. Hales, Lewis and Silverstone (2006) reported that in 2004/05, 44% of crimes involving firearms were criminal damage offences, 35% of offences were violence against the person and 16% were robberies. These figures include crimes where air weapons were used. Excluding the use of air weapons, the figures are revised to 53% being violence against the person, 33% robberies, 6% criminal damage and 3% burglaries. These percentages are illustrated in Figure 2-1.

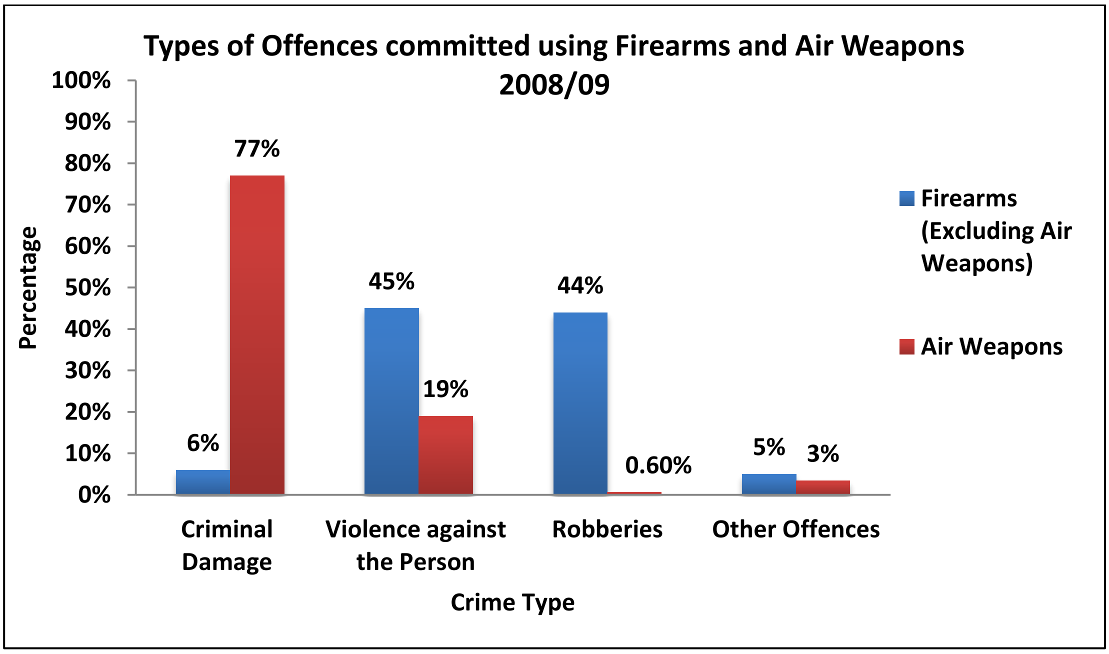
Figure 2-1: Types of Offences Committed using Firearms 2004/05



Source: (Hales, Lewis and Silverstone, 2006).

Recent figures published by the Home Office (Smith et al, 2010) show that in 2008/09 the types of crimes committed using non-air weapons were violence against the person accounting for 45%, robbery accounting for 44% and criminal damage accounting for 6%. Criminal offences involving air weapons were distributed as follows; criminal damage accounting for 77% of offences and violence against the person accounting for 19% of offences and robberies accounting for 0.6% of offences. These percentages are presented in Figure 2-2. There are no combined percentages available in this particular study for the year 2008/09 (Smith et al, 2010). The statistics presented by Smith et al (2010) and Hales, Lewis and Silverstone (2006) refer to crimes in England and Wales. It is entirely possible that the manifestation of crimes involving firearms differs in other countries (Krug et al, 1998).

Figure 2-2: Types of Offences Committed using Firearms and Air Weapons 2008/09



Source: (Smith et al, 2010)

The geographical distribution of gun crime is interesting to study and has implications for resource allocation of any interventions. Smith et al (2010) showed that excluding the use of air weapons, gun crime in the UK was concentrated in London, Manchester and Birmingham. However, because of the serious nature of offences involving firearms, local media report extensively. This gives the impression that gun crime is more widespread outside of London, Manchester and Birmingham (Nottingham Post, 2010 as one example). Because of their very nature gunshot wounds cause serious injuries and consequently have a serious impact on victims. Gunshot wounds can be problematic for the health services to deal with as many doctors working in the National Health Service in the UK have limited experience of treating gunshot wounds meaning that the impact of these crimes can be much higher and serious injuries may become fatal (Cutts, Bridle and Bleetman, 2006). A Home Office study looking at crimes committed in 2004/05 suggested that 24% of all crimes involving any type of firearm resulted in injury to the person (Hales, Lewis and Silverstone, 2006). In 2008/09, 17% of crimes involving firearms resulted in an injury to a person. (Smith et al, 2010). This appears to suggest a decline in the number of firearms incidents resulting in injury but the harm caused by firearms incidents is still high.

2.1.2 Incidence of Gun Crime in the UK – Research other than Official Statistics

Whilst official statistics are useful, they are affected by the fact that many crimes involving firearms are not reported. This creates problems including a gap in intelligence and the potential for the levels of gun crime to be underestimated. Consequently, interventions may be scaled back because the problem is perceived to be small. Research methods that venture beyond the examination of official statistics can be helpful in addressing this problem. Examples are the examination of medical data and interviews with offenders. These additional data enable official statistics to be contextualised and an understanding to be gained of the comprehensiveness of official data.

Persad et al (2005) examined the medical records of people admitted to a London hospital with gunshot wounds to ascertain if the number of people admitted to hospital correlated with police statistics. The authors were examining the incidence of injuries, any medical complications arising from them and the clinical experience in treating these injuries. They looked at 70 injuries inflicted on 61 individuals over a five year period between 1998 and 2002 and concluded that their data correlated well with police data. There had been a fourfold increase in injuries over the time period examined. A similar study was undertaken retrospectively by Crewdson et al (2009). The authors examined data collected at a pre-hospital care trauma service in relation to stabbings and shootings in London. The data covered a sixteen year period (1991 – 2006) and suggested there had been an 11% increase in gunshot wounds sustained. The authors point out that this increase is not supported by data from other sources such as the British Crime Survey and the Metropolitan Police. Crewdson et al (2009) suggest that this is because this data include crimes where guns were used but no injuries were sustained. It may be that this has skewed the data and injuries caused by firearms have actually increased.

Data gained from hospitals and medical treatment centres offers an interesting alternative source of data that can be compared with police and government data. In the UK doctors are now required to report all cases of gunshot wounds and stabbings to the police (Morris, 2009). Similar studies to that conducted by Pershad et al (2005) have been conducted in Estonia (Lepik and Poldsam, 2007), Italy

(Verzeletti et al, 2009), Sweden (Karlsson et al, 1993) and Germany (Karger et al, 2002). These initiatives may help to fill in gaps in statistics created by unreported crime.

Official police statistics and medical data are useful in quantifying the extent of gun crime in the UK. However, these statistics will not include the extent to which offenders possess and use firearms when no injuries have occurred. Bennett and Holloway (2004) attempted to fill this knowledge gap by interviewing arrestees. The research covered sixteen custody suites in England and Wales and took place over three years between 1999 -2002. It involved interviewing 1570 arrestees in relation to gun ownership. Unfortunately the authors do not state what offences the arrestees were detained for. However, Bennett and Holloway (2004) found that 20% of participants had possessed an illegal gun in their lifetime and that 60% of these guns were handguns. Of the 20% of participants that had possessed an illegal gun, 26% reported that they had carried a gun during the commission of an offence. Bennett and Holloway (2004) suggest that interventions that aim to reduce gun crime should target the criminals that are using and possessing illegal firearms but that interventions will not be effective unless all the characteristics that underlie gun possession in the criminal population are understood (Bennett and Holloway, 2004). Table 2-1 presents a summary of the main findings of research conducted examining gun crime in the United Kingdom.

Table 2-1: Summary of Main Findings Concerning Gun Crime in the UK

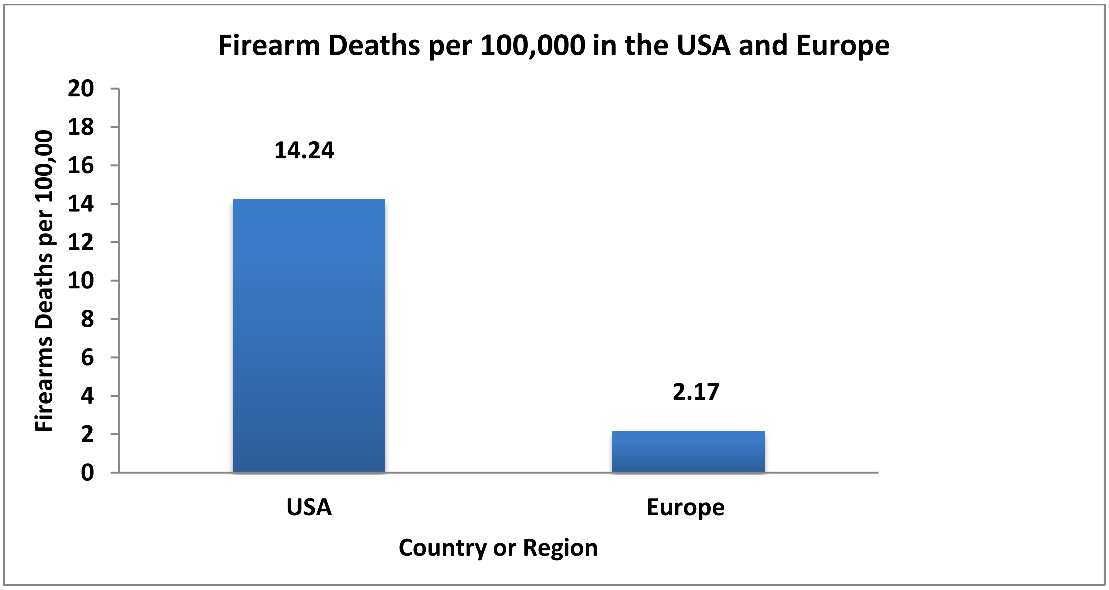
Author(s) and Year	Research Method and / or Data Source	Main Findings
Smith et al (2010)	Recorded crime Statistics	In 2008/09 Gun Crime accounted for 0.3% of all recorded crime in England and Wales representing over 14,000 crimes and 432 fatal or serious injuries. Excluding air weapons, the number of offences recorded was 8,208. Compared to the previous year, offences involving firearms fell by 18%. Excluding Air Weapons, firearms offences fell 17%. Gun crime is concentrated in London, Manchester and Birmingham. 17% of crime in 2008/9 involving any type of firearm resulted in injury to the person.
Hales, Lewis and Silverstone (2006)	Recorded crime Statistics	Offences committed using firearms are varied and there is a difference in offences committed using firearms and air weapons. 24% of crimes in 2004/5 involving any type of firearm resulted in injury to the person.
Persad et al (2005)	Medical records of people admitted to hospital with gunshot wounds.	The data correlated well with police statistics. There was a fourfold increase in injuries over the time period studied (1998 – 2002).
Crewdson et al (2009)	Data from a pre hospital trauma centre in London.	There was an 11% increase in gunshot wounds over the sixteen year period studied (1991 – 2006).
Bennett and Holloway (2004)	Interviews with arrestees.	20% of participants had possessed an illegal gun and 60% of these guns were handguns. Out of this 20%, 26% had carried a gun during the commission of an offence.

2.1.3 Gun Crime outside the UK

Research into gun crime in the UK is useful and important. It is also important to recognise that different countries will have different manifestations of gun crime depending on many variables. These might be cultural, economic, population and legislative differences. For this reason, research conducted examining countries outside the UK is also considered. This section examines gun crime that occurs outside the United Kingdom. There are two types of research considered in this section. The first is comparative analysis of crimes involving firearms between different countries. The second considers gun crime from the perspective of a single country. The countries considered are Canada, Republic of Ireland and the West Indies as published research was available examining these countries in detail.

There is a great deal of variance in the nature and characteristics of gun crime outside the UK. This is due to a number of factors and the extent of the variance is well demonstrated by Krug et al (1998) who compared the rate of firearm deaths across 36 countries. Krug et al (1998) used the World Bank income classification system which is based on the Gross National Product of a country. Only countries classified in the high income or upper middle income groups were approached to participate. The rationale for this decision was that these countries were more likely to have data that would be of sufficient standard. Participating countries also had to have a population of over one million. Forty six countries met the inclusion criteria and 36 responded to the request for data. The study considered fatalities from a one year period and resulted in data being provided concerning 88,649 firearm deaths. The main finding was that the USA was unique in several ways. Firstly, the USA had the highest rate of deaths caused by firearms at 14.24 per 100,000 which is 5 to 6 times higher than that in Europe[1] which had a death rate of 2.17 per 100,000. This is illustrated in Figure 2-3.

Figure 2-3: Deaths Caused by Firearms in the USA and Europe



Source: (Krug et al 1998)

The USA also had the highest rate of homicides and suicides committed using a firearm. The high mortality rate in the USA has led to much research and commentary concerning firearms deaths and the underlying reasons behind the high mortality rate. Spitzer (1998) suggested a number of factors that contribute to a gun culture in the United States including the fact that many Americans own guns for recreational and hunting purposes. There has also been a historical link between the role of

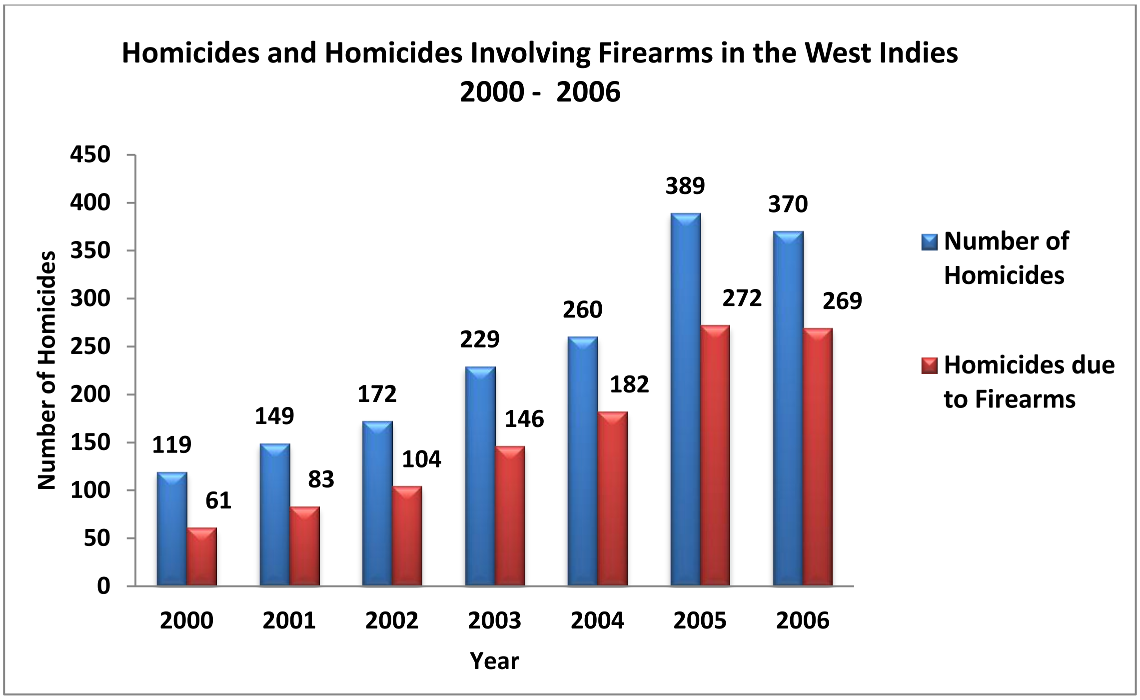
[1] In this research, the European countries that responded with data were: Estonia, Northern Ireland, Finland, Switzerland, France, Norway, Austria, Portugal, Belgium, Slovenia, Italy, Denmark, Sweden, Greece, Germany, Hungary, Ireland, Spain, Netherlands, Scotland, England / Wales.

guns and maturity. Spitzer (1998) also argued that the constitutional right of American citizens to bear arms makes any restrictive regulation politically difficult. Amongst the countries considered by Krug et al (1998), there were four Western nations that had high firearm mortality rates. These were the USA, Brazil, Mexico and Argentina. Firearm mortality was contrastingly low amongst the five Asian nations that took park. These were Japan, South Korea, Hong Kong, Singapore and Taiwan. Krug et al (1998) suggested that in order to explain the variance between countries, three factors should be taken into account. These are the homicide rate, the suicide rate and factors that influence the use of firearms – the usefulness of data on suicides in considered later in this section. Finally, Krug et al (1998) suggested that the low rates of firearms deaths in Asia showed that such deaths can be prevented and that it is not impossible for other nations to achieve a low firearm death rate.

The data gathered by Krug et al (1998) provided a valuable comparative insight into gun crime in different countries. However, one of the disadvantages of the research conducted by Krug et al (1998) is that it only provided a snapshot of a single year in each country. To identify trends and patterns in the data it is useful to consider the official statistics produced by governments of different countries.

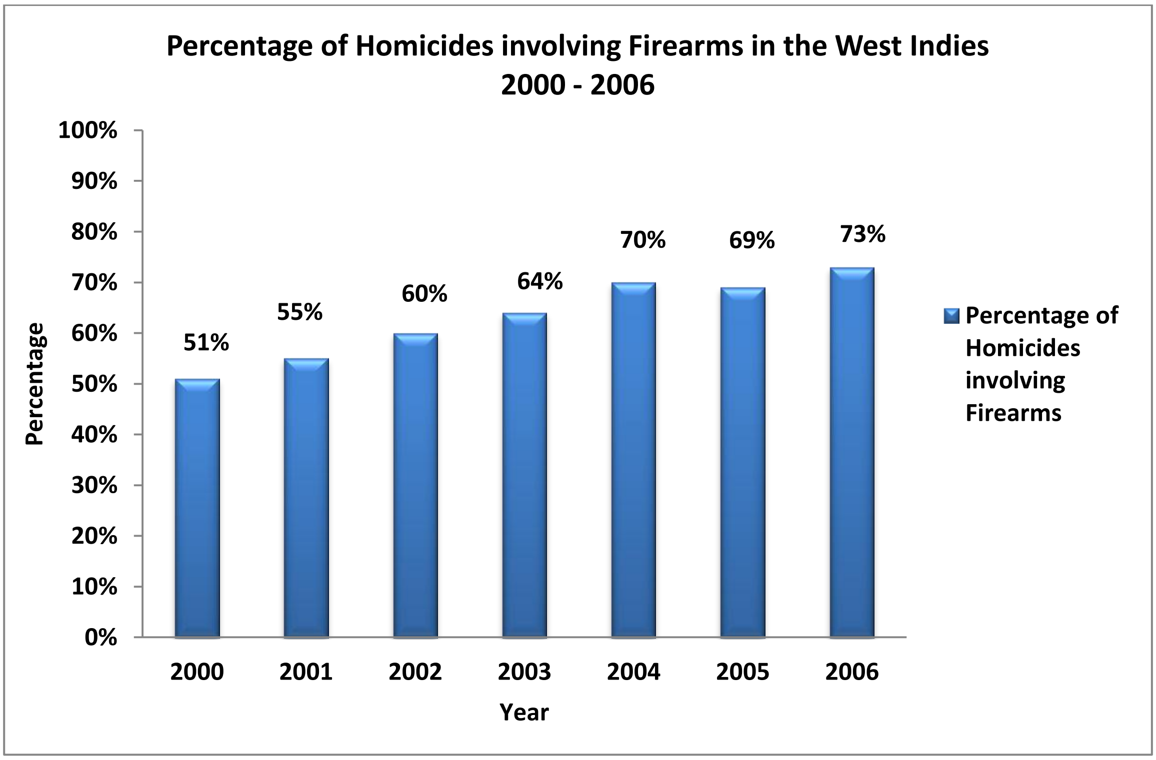
One such example is the research conducted by Agozino et al (2009). The authors attempted to explain the problems caused by gun crime in the West Indies in the context of the interaction between guns, crime and social order. The authors examined data collected by the Trinidad and Tobago police on 1688 homicides over a six year period between 2000 and 2006. The data showed that the involvement of firearms in homicides rose steadily over the six years as did the actual homicide rate. This is shown in Figure 2-4. The year by year percentage increase is shown in Figure 2-5. The data also suggested that homicides committed with a firearm were less likely to be solved than other homicides. Agozino et al (2009) suggested two reasons for these observed trends. Firstly, the weaponisation of society – this refers to the influx of small arms into a civilian society. The second factor was a rise in retaliation murders. Agozino et al (2009) suggested that these two factors were interlinked and that the availability of small arms or weaponisation facilitated retaliation murders.

Figure 2-4: Homicides and Homicides Involving Firearms in the West Indies 2000 -2006



Source: Agozino et al (2009)

Figure 2-5: Percentage of Homicides in the West Indies that Involved Firearms 2000 – 2006

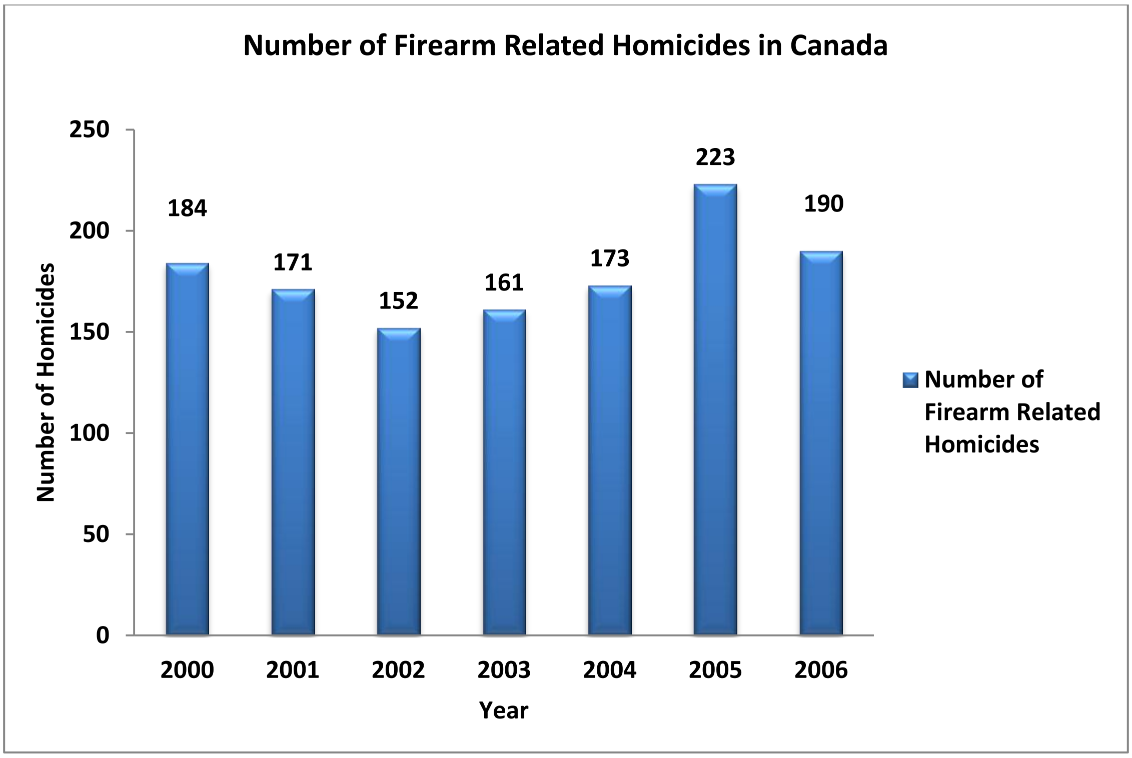


Source: Agozino et al (2009)

Agozino et al (2009) suggested that the weaponisation of societies has accompanied imperialism and the problems posed by gun crime in the Caribbean must be understood in the wider context of colonialism. They suggested that prevention of firearm deaths in the Caribbean lies in focussing effort on reducing the weaponisation of the area.

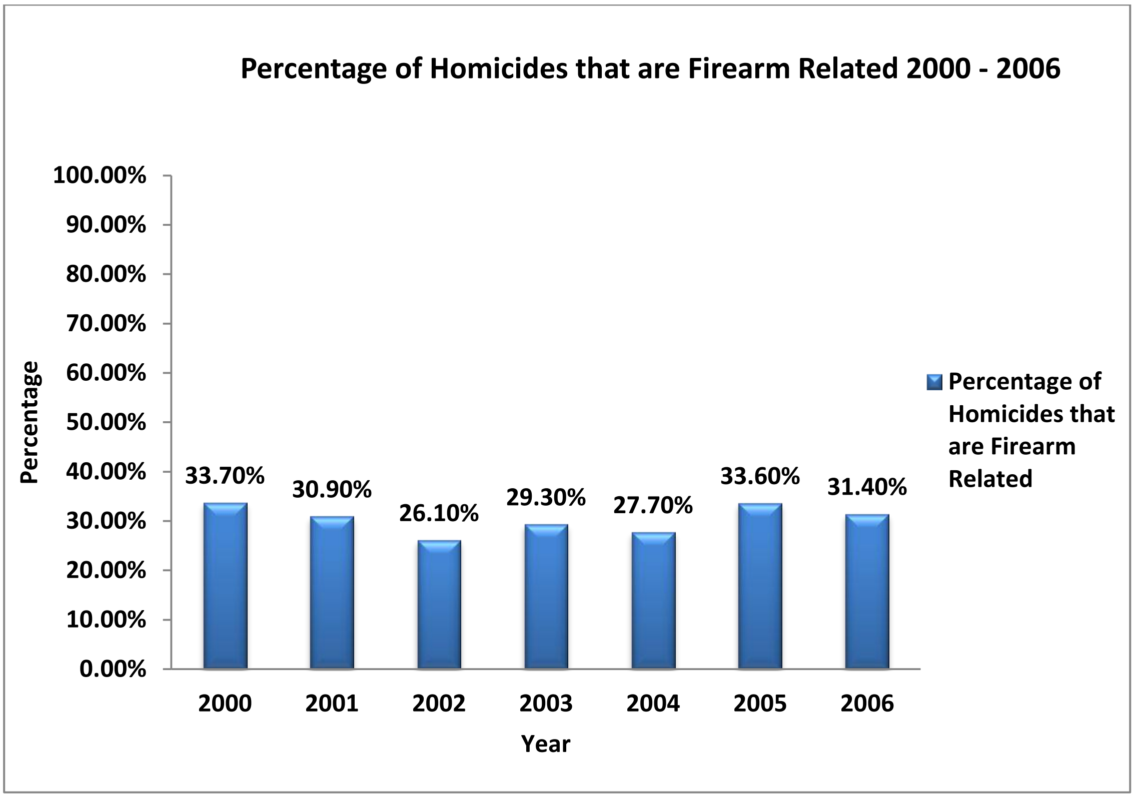
Contrast the situation in the Caribbean with that in Canada. Sheptycki (2009) considered Canadian crime statistics such as those reported by Dauvergne and De Socio (2008), the coverage given to firearm offences in Canada by the media and firearm legislation. Sheptycki (2009) examined crime statistics which showed a declining crime rate and homicide rate. Despite this, Canadians still reported a higher fear of crime than their American counterparts. Sheptycki (2009) attributed this to ways in which the Canadian media reported crime. They tended to keep a story in the headlines longer and report non-local events. These factors in combination magnified the perceived threat of crimes involving guns (Sheptycki, 2009). Offences involving firearms are actually very rare in Canada and are mainly committed by a small minority of criminals involved in other criminal activities. Despite this evidence, Sheptycki (2009) reported a Canadian perception of a problem with gun crime. Figure 2-6 shows the number of firearm related homicides for 2000 – 2006 in Canada and Figure 2-7 shows firearm related homicides as a percentage of all homicides.

Figure 2-6: Firearm Related Homicides in Canada 2000 – 2006



Source: Dauvergne and De Socio (2008)

Figure 2-7: Percentage of Homicides that are Firearm Related 2000 – 2006

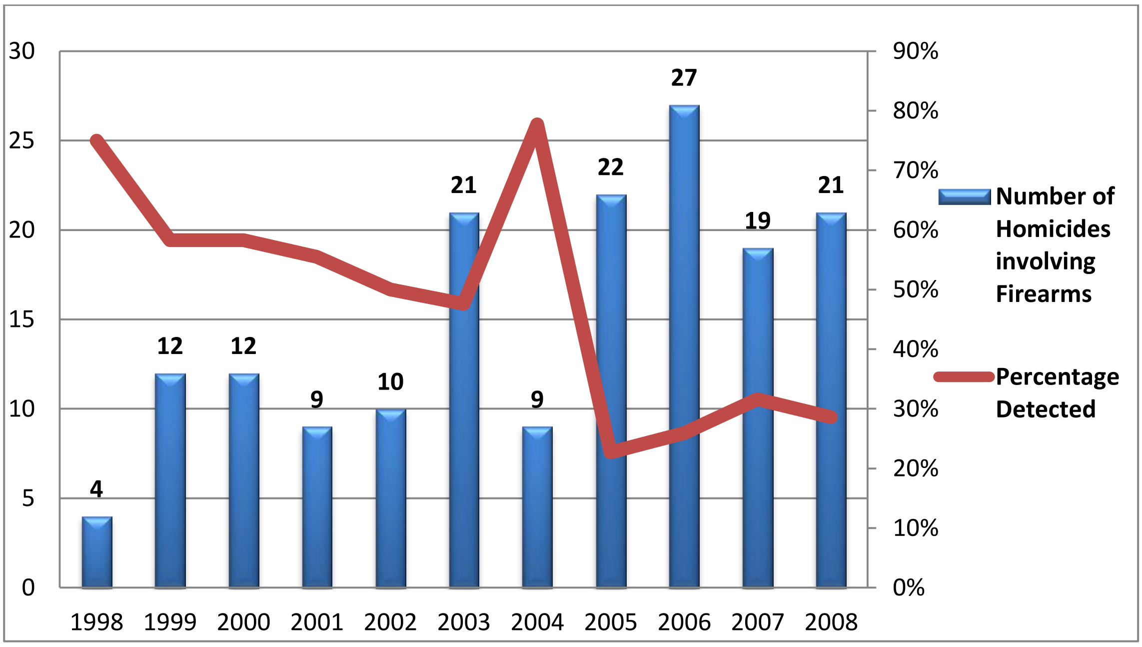


Source: Dauvergne and De Socio (2008)

Campbell (2010) described the nature and extent of gun crime in the Republic of Ireland. The main trends in the Republic of Ireland were a rise in homicides involving firearms and a fall in the detection rate of these offences. Agozino et al (2009) also reported that homicides involving firearms were less likely to be solved. The number of offences in Ireland reported to the Police where a firearm was discharged rose from 163 in 2001 to 224 in 2008. Over the same time period there was a notable decline in detection rates. These figures are illustrated in Figure 2-8. Despite the fact that the West Indies and the Republic of Ireland are different countries with different contexts, there is a common finding –crimes involving firearms appear to be difficult to solve. This could be for a number of reasons including the reluctance of victims and witnesses to testify. It could also be due to forensic issues. The issues surrounding the forensic examination of ballistics items are discussed in a later section but the findings of Agozino et al (2009) and Campbell (2010) suggest that there may be areas where forensic ballistics could be improved.

Campbell (2010) also compared the percentage of homicides committed with a firearm in Ireland to statistics for England and Wales. Between 1998 and 2008 the proportion of homicides committed using a firearm in Ireland was twice to five times higher than that in England and Wales suggesting a problem in Ireland and the need for new measures. It is possible that this finding can be at least partially attributed to the partial weaponisation of Ireland as a result of sectarian violence. The difference between England and Wales and Ireland is especially important to consider given the difference in the population size.

Figure 2-8: Number of Homicides in Ireland and Detection Rates 1998 - 2008



Source: (Campbell, 2010)

Krug et al (1998) identified the fact that the suicide rate is interlinked with the overall firearm mortality rate in a particular country alongside the homicide rate and the availability of firearms. Research on suicides is considered to ascertain the relevance to gun crime issues. Sarma, Griffin and Kola (2010) conducted research examining firearm assisted suicides in the Republic of Ireland. They found that between 1980 and 2003 there were 725 firearm assisted suicides representing 8.48% of all suicides. Males were more likely to use a gun when committing suicide and firearm suicides were closely linked with living in a rural area. The statistics on firearm suicides are presented in the context of the judiciary changes that have recently occurred in the Republic of Ireland. Sarma, Griffin and Kola (2010) explained how the law in the Republic of Ireland regarding the possession of firearms was very strict up until 2004 when there was a relaxation of legislation. They outlined concerns around firearm assisted suicides in the context of these laws now being less stringent. In terms of prevention, the authors suggested two approaches. Firstly to ensure that requirements for safe and secure storage of firearms are included in legislation minimising access to legally held firearms. Secondly, the authors suggested that people suffering from mental illness should be restricted from gaining access to firearms legally. Although the research presented refers to suicides, the recommendations made on prevention can be applied to the use of weapons in crimes especially given the link between homicide, suicide and firearms suggested by other authors such as Shaw et al, (2005) and the statistical insights suicide figures can provide (Krug et al, 1998). The research on suicides presented here is in the context of different manifestations of gun crime in different countries and the overall death rate. A further discussion of suicides is presented in the next section of the literature review addressing factors relevant to individual people and their involvement in gun crime.

Research conducted that examines deaths caused by firearms shows that there is a complex set of issues that underlie the manifestation of gun crime in different countries. These include the historical and cultural context of a country as well as legislation and economic circumstances specific to that country. Research to date suggests that these factors should be taken into account when planning interventions to reduce gun crime. However such research does not address the underlying reasons as to why individuals become involved in crime and why guns are used. Gun crime has been discussed in the context of gang involvement extensively in the literature by Vaughan et al (1996), Bullock and Tilley (2002), Decker and Curry (2002), Marshall, Webb and Tilley (2005), Hales et al (2006), Hayden et al (2008) and Hallsworth and Silverstone (2009). The next section presents theories on gang involvement and discusses why individuals become involved in gangs and associated criminal activity. Theories of gang involvement are discussed along with more recent research that aims to provide evidence to support the theories discussed.

2.2 - Gun Crime: Types of Offender

2.2.1 Guns, Gangs and Drugs

As already discussed, crimes involving the use of firearms occur worldwide (Krug et al, 1998). The exact nature and extent of the problems caused by crimes involving firearms varies dramatically between countries and sometimes within countries. Influencing factors include geography, demographics, social conditions and legal issues (Agozino et al, 2009; Sheptycki, 2009; Campbell, 2010). All play a part in defining the nature of gun crime in any given country. The use of guns has been associated with gang culture and the illegal drugs market. The extent to which the use of firearms, gangs and drugs are entwined is difficult to unravel. It is likely that there is a great deal of overlap between offenders that use firearms, offenders that are in gangs and offenders that sell drugs.

In the United Kingdom, the use of firearms has often been linked to gang culture and associated criminality (Bullock and Tilley, 2002; Bullock and Tilley, 2008; Robert and Innes, 2009) and as a result research has been undertaken to ascertain if this is actually the case. Until relatively recently (Hayden et al, 2008; Hallsworth and Silverstone, 2009) there was a lack of research available that focussed on UK gangs (Marshall, Webb and Tilley, 2005). Instead, research conducted on gangs in America had been used despite obvious cultural differences. However, there is a definitional difficulty that arises when discussing gang related issues (Marshall, Webb and Tilley, 2005; Hales et al, 2006). A discussion on what constitutes a gang is beyond the scope of this thesis. Instead, a gang is considered in the context of "(loosely) organised crime structures, such as drug dealing networks. Significantly, these collectives or gangs provide a focal point for violence, including long running feuds that draw in gang members and their families." (Hales et al, 2006: 13). A detailed discussion on the link between guns and gangs is presented later in this chapter.

Recent research on various aspects of gang involvement provides plenty of areas for discussion. Prior to considering recent arguments it is prudent to discuss theories of criminality which attempt to explain why people get involved in criminal activity in the first place. Many of these theories have been applied to gang membership and offer a good insight as to the underlying reasons behind gang related criminality. This section describes theories that attempt to explain why people turn to crime. These theories are subsequently applied to gang involvement and the illegal use of firearms.

2.2.2 Theories of Crime and Gang Involvement

Wood and Alleyne (2010) present an overview of different theories of crime and the relationship between these theories and gang involvement. They explained that gang research started in earnest with the work conducted by Thrasher (1927). This research concerned adolescent boys in Chicago and explored the reasons for their involvement in gangs and argued that economic deprivation led to social disorganisation. This in turn led to young boys becoming involved in gangs. Thrasher (1927) theorised that economic disadvantage led to normal social organisations such as school and church becoming less able to satisfy and therefore unable to control the population. This work also argued that one of the drivers behind the failure of existing social structures to satisfy the population was the fact that many people living in these deprived areas were immigrants. These people were unable to help their children adapt to their new surroundings because of a lack of understanding of the local culture. Thirdly, it was suggested that gangs could offer children and young people more excitement than existing social structures.

Shaw and McKay (1931) developed Thrasher's (1927) research and argued that economically and socially deprived areas encouraged criminal activity which transferred to young people living in those areas. They argued that adults having low levels of authority over children resulted in children being involved with gangs, as gangs offered a social support system in a disorganised community. Shaw and McKay (1931) also suggested that criminality can be passed through generations causing long term involvement in gangs in certain areas.

A disadvantage of the research conducted by Thrasher (1927) and Shaw and McKay (1931) is the suggestion that criminality is associated with low socioeconomic class. Other researchers have argued that crime is committed by all kinds of people and is not restricted to working class people. Sutherland, Cressey and Luckenbill (1992) explained how it was recognised that associating with other people that are accustomed to criminal behaviour and consider this behaviour normal, can cause these attitudes to be passed on. This is the essence of the differential association theory and supports the argument that criminal behaviour is a learned behaviour and that the behaviour is learned from people that are important to the individual. It is also important to note that the ways in which criminal behaviours are learned are not different to the ways other behaviours are learnt. This theory also argues that engaging in criminal behaviour is a result of exposure to such activity and that there will be a tipping point where there is more exposure to criminal activity and attitudes and this will then lead to the commission of more crime. The relevance is that the small social groups that provide these social norms are often gangs.

Strain theory developed by Merton (1938) argued that society sets goals for individuals but only a limited number of people can actually achieve them. This leads to problems because many people cannot achieve these aims and people then adapt to these expectations by committing crime because the lawful avenue to achieve society's ideal is not available to them. Cohen (1955) took this theory a step further and applied it to gang membership suggesting that the strain for gang members is status frustration where goals are achieved through instant gratification and violence. Cohen (1955) also argued that young people may realise they do not have access to the economic means or social structures needed to progress and achieve society's norm. They will, therefore, turn to gangs because this approach offers a chance to achieve a certain status. Theory of differential opportunity is similar to strain theory but adds the additional argument that people must have the opportunity to learn illegal behaviour. Cloward and Ohlin (1960) argued that middle class children simply do not have access to such illegal behaviours and therefore do not have the opportunity to learn them.

Although all of the theories offer different insights and explanations for criminal behaviour, there are some factors which stand out as important. These are social deprivation, failure to achieve goals and exposure to criminal activity. A summary of the theories discussed is presented in Table 2-2. The next section looks at recent research conducted into gangs to ascertain if any of the arguments relating to theories of crime are relevant.

As previously discussed, until recently there was a lack of UK focussed research on gangs (Marshall, Webb and Tilley, 2005). However research examining the prevalence of gun crime has resulted in more research because of findings such as that from a study conducted by Bullock and Tilley (2002). They estimated that 60% of shootings in Manchester were gang related. Because this percentage was so high, more research has been funded and conducted to address the gang problem in the UK.

Hayden et al (2008) looked at the wider social context of gang members and crimes committed using firearms. In this research, eighty young men convicted of firearms offences in England and Wales were interviewed with the aim of exploring their backgrounds to ultimately prevent crimes involving firearms. Hayden et al (2008) found that the vast majority of offenders they interviewed were characterised by deprived family and educational backgrounds. They were more likely to have been excluded from school and had poor work histories. A link was also found with living and growing up in socially deprived areas with few opportunities. Hayden et al (2008) also found that there was no clear distinction between victims and offenders. Half of the interviewees had been threatened with a gun and 36% had been shot themselves. Hayden et al (2008) pointed out that the criminal lifestyle can appear as lucrative and legitimate to young people living in deprived communities and that prevention strategies should take this into account and provide realistic alternatives. Hayden et al (2008) provided further evidence of a correlation between gun crime, young men and social deprivation.

Hallsworth and Silverstone (2009) conducted interviews with offenders and practitioners and also reviewed relevant literature. They conclude that terms such as "gun culture" or "gang culture" are too general to be helpful in reducing crimes committed with firearms. Instead they suggested that the use of guns can be split into two broad categories. The first concerned the use of guns by professional criminals. This group are proficient in the use and disposal of firearms and use them sparingly. The second category consists mainly of young men from deprived backgrounds committing crimes frequently to make money. They suggested that these offenders are following a “street code” and whilst not carrying firearms routinely, they will resort to using them to resolve disputes. The findings of Hallsworth and Silverstone (2009) also suggested that social deprivation is an important contributing factor to the prevalence of gun crime and this has also been found in other research such as that conducted by Shaw et al (2005) and Hayden et al (2008).

The association between guns and drugs is often made in the media (Press Association, 2010; Manchester Evening News, 2010). These news stories reinforce the perception that gangs, guns and drugs are interlinked. It is interesting to examine research that has been conducted to establish if this association is merited. A study conducted by Hales et al (2006) which involved interviewing eighty offenders that had been convicted of crimes involving firearms, strongly supports this argument. The authors stated that the “illegal drugs markets represent the single most important theme in relation to the use of illegal firearms” (Hales et al, 2006: 65). This study identified four particular event types where firearms and the illegal drugs market interact. Firstly, the robbery of drug dealers often involves firearms. The underlying explanation for these crimes is that these people deal in goods that have a high value (cash and the drugs themselves) and they are highly unlikely to report the robberies to the police as this would involve implicating themselves in drug dealing activity. The second manifestation of the interaction between firearms and drugs identified by Hales et al (2006) is territorial disputes. A typical scenario might be a crime involving firearms committed against people drug dealing on another dealers’ “patch”. The third type of usage of firearms concerns protection from robberies and from attacks that may occur. The fourth type of usage is referred to as “sanctioning” for example, recovering debts, or enhancing a fearsome reputation of the drug dealer. The underlying explanation for the link between drugs and guns offered by Hales et al (2006) is that the usual criminal justice avenues are not available to people involved in the drugs as they are themselves involved in illegal activity so they use guns in the ways previously described. Interestingly, Hales et al (2006) found that half of the offenders interviewed belonged to a gang but importantly many of the interviewees insisted that they were not part of a gang but that outsiders might perceive them as being part of a gang. This finding again supports the link between crimes involving firearms and gangs and drugs.

The findings of Hales et al (2006) do appear elsewhere in the literature. One such example is research conducted by McKeganey and Norrie (2000) who examined the link between weapon carrying (all types of weapons) and the use of illegal drugs in Scotland. This study used self-report methods, and found that weapon carrying was strongly associated with taking illegal drugs in Scotland. Unfortunately the results presented by McKeganey and Norrie (2000) did not provide specific details on firearms but the link between drugs and weapons is nevertheless relevant. Other research has revealed a link between excessive alcohol consumption and firearms. Hemenway and Richardson (1997) found that people who owned semi-automatic or automatic weapons were more likely to engage in binge drinking, a finding they describe as "disturbing" (Hemenway and Richardson, 1997: 287). Illegal drugs and alcohol reduce inhibitions and make a person more likely to perceive neutral situations as threatening. The addition of firearms to this context arguably makes the use of them-intentionally or accidentally –more likely. Krug et al (1998) suggested that three factors influenced the firearm mortality rate with one of them being the availability of firearms. The link with drugs and alcohol is important because such substances lower inhibitions and if firearms are readily available, arguably a firearm related fatality is more likely.

Although carried out in New York, research conducted by Vaughan et al (1996) lends some support to the argument made by Thrasher (1927) which linked gang membership and immigrant families. Vaughan et al (1996) examined weapon carrying amongst predominantly Hispanic youths in New York which, at the time of research, was the fastest growing immigrant group. It was found that 21% of people carried a weapon and of these individuals, 28% carried a gun. It was also found that 41% of all respondents knew someone that had been shot. Although Vaughan et al (1996) did not speculate on causal factors they conceded that their research provided an important insight into the group studied. It also showed that, in this particular group, participants' exposure to weapons and guns was particularly high. However, this research should be treated with caution as it is likely that underlying factors such as deprivation and poverty were linked to criminal activity.

The research presented in this section examines human factors that contribute to gun crime such as general criminality, gang membership and involvement in illegal drugs. However, it has been suggested that there is a link between the availability of firearms in a given population and the rate of deaths whether homicides, suicides or accidental deaths. Data on suicides whilst initially seeming irrelevant, on closer inspection can provide valuable information. Research has suggested a link between murder and suicide both in terms of observed trends and the demographic committing murder and suicide and the demographic who are victims of murder and suicide. The previous section briefly discussed suicides from the perspective of the overall death rate in a particular country. The discussion of suicides here is in a different context, from the perspective of an individual whether as a victim or perpetrator of murder or suicide and the factors that contribute to this link.

Shaw et al (2005) examined the murder rate in Britain between 1981 and 2000 and found that young men were most likely to be involved in murders both as offenders and victims correlating with the demographic group most likely to commit suicide. A correlation was also found between social inequality and murder rates. The authors concluded that, "as rates of suicide and homicide of young men have both risen, this suggests that they care increasingly little about themselves or others." (Shaw et al, 2005: 53.) This supported the findings of Hayden et al (2008) who also found a link between people committing crimes involving firearms and social deprivation. Sorenson and Berk (1999) also replicated this finding in Los Angeles. They examined data on homicide suspects and suicide victims and found that males and people under the age of twenty one were the most likely group to kill themselves or someone else using a firearm.

A correlation between murder and suicide has important implications for the prevention of such offences especially where firearms are involved. A correlation between murder and suicide suggests that reducing the availability of firearms may actually decrease both murders and suicide committed with firearms. Other research has also hinted at a correlation between the availability of firearms and the rate of suicides (Krug et al, 1998; Andres and Hempstead, 2011).

The next section addresses the problems discussed so far and focuses on strategies to reduce gun crime.

2.3 - Gun Crime Reduction Strategies

This section aims to discuss the ways in which gun crime can be reduced using the findings from research conducted in this area. One of main ways that government have attempted to reduce and prevent crimes involving firearms is through legislation restricting or banning outright access to firearms.

2.3.1 Firearms Legislation in the UK

The United Kingdom has some of the most restrictive and complicated laws in the world legislating on the ownership and possession of firearms and ammunition (Warlow, 2007). Illustrative of this is the fact that there are 55 offences that can be committed with a firearm before it is pointed at anyone or discharged (Squires, 2008). Firearms legislation in the UK can be traced back to 1870 when it became necessary to hold a licence in order to carry a firearm outside one’s home. The Pistol Act of 1903 followed which denied firearm ownership to drunk or insane people. This Act also introduced the requirement of a licence for short barrelled weapons (handguns). The number of firearms in the UK increased after the First World War as soldiers returned home with their battlefield weapons. This led to more legislation being introduced in the form of the 1920 Firearms Act. This introduced a registration system and allowed the police to deny a licence to any unsuitable persons. The Firearms Act in 1937 almost fully banned automatic weapons. In 1967 the Criminal Justice Act consolidated existing gun laws and allowed the Home Office to set fees for shotgun licences.

There have been two serious events in the UK where multiple murders were committed using legally held weapons. These are commonly referred to as the “Hungerford Massacre” (Guardian, 1987) which occurred in 1987 and the “Dunblane Massacre” (Guardian, 1996) which occurred in 1996. As both of these events involved legally registered firearms, they both led to major changes in UK firearms legislation. Following the Hungerford Massacre in 1987, further legislation was introduced (the Firearms (Amendment) Act 1987) that banned semi-automatic and pump-action rifles; weapons that fire explosive ammunition and elevated pump action and self-loading rifles. Registration for shotguns was made mandatory and they were required to be kept in safe storage. The Dunblane Massacre led to the Firearms (Amendment) (No 2) Act 1997 which banned all handguns above .22 calibres. The Violent Crime Reduction Act (VCRA) 2006 introduced more restrictions particularly concerning imitation weapons. This Act made it an offence to manufacture, import or sell realistic imitation guns, it doubled the maximum sentence for carrying an imitation gun to twelve months and made it a crime to fire an air weapon beyond the boundary of a premises. It also raised the age limit for buying or possessing an air weapon from 17 to 18. However, the implementation of this act has been somewhat problematic due to loopholes in the law that still enable the purchase of imitation weapons. There was also concern as to how well the VCRA was communicated to the agencies responsible for implementing it (Wheal and Tilley, 2009). Further mass shooting events have occurred in the UK. In June 2010 Derrick Bird shot twelve people and then killed himself in Cumbria with legally held firearms (BBC, 2010a). In July 2010 Raoul Moat shot three people before killing himself (BBC, 2010b). These events have reawakened the debate on gun control in the UK and a Home Affairs Select Committee has been convened to discuss the issues raised by these two events.

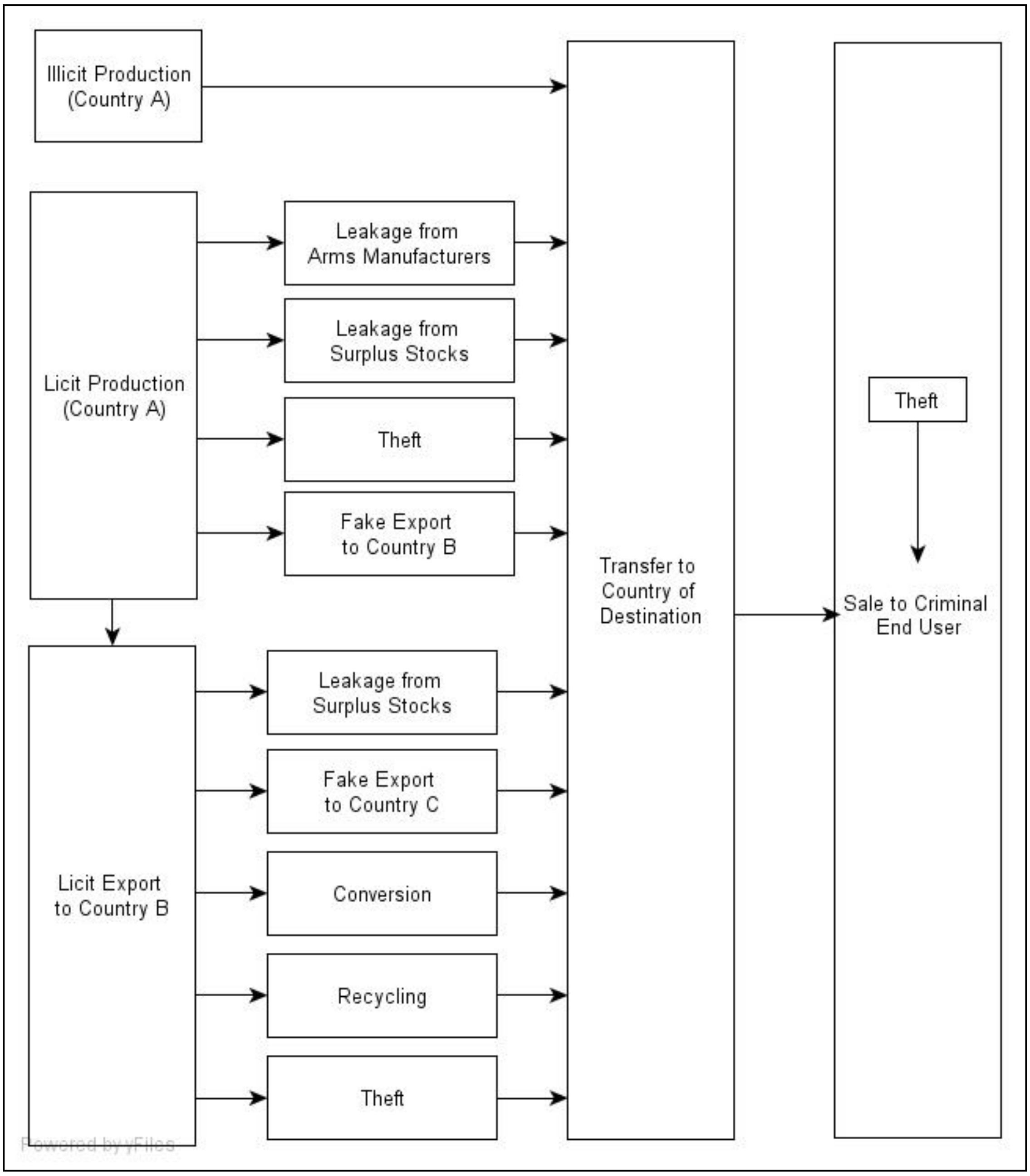
2.3.2 Consequences of UK Legislation

Warlow (2007) explained that after the Hungerford and particularly the Dunblane massacre in 1996 stricter laws were introduced to control the ownership of guns in the UK. The recommendations from the Dunblane Inquiry did not recommend a full ban on handgun ownership but public and political opinion was so strong that legislation banning handguns was introduced (Cullen, 1996). As part of this legislation, guidelines were agreed so that existing weapons that were legally owned could be deactivated and be therefore kept legally. De-activating a firearm involves modification so it can no longer fire ammunition usually by removing key parts. However, as a result of these laws and the increasing number of deactivated weapons available, a new criminal trade emerged in reactivating firearms. Firearms can be reactivated by replacing the components that have been either removed or deliberately damaged as part of the deactivation process. Warlow (2007) outlined how the use of reactivated firearms quickly became problematic across the United Kingdom. As the number of reactivated firearms increased so did the quality of the reactivation processes utilised by criminals. It is now that case that a large number of reactivated firearms are in circulation in the UK (Warlow, 2007). The problem outlined by Warlow (2007) shows that specific factors such as legislation can affect the distribution of firearms and the resulting forensic processes. Warlow (2007) demonstrated that an understanding of the exact nature and characteristics of gun crime is essential to ensure that interventions such as the introduction of new legislation are targeted correctly and do not have unintended consequences such as displacing or creating a new manifestation of the problem. Warlow (2007) also highlighted the fact that continued assessment of the impact of any interventions is critical to enable judgements to be made on the effectiveness of the policy.

2.3.3 Supply, Distribution and Trafficking of Firearms

The trade in illegal firearms has become a global problem for law enforcement agencies. Within the European Union, illegal firearms are often intended for criminal use in member states rather than passing through member states to be used in countries outside the European Union. Spapens (2007) suggested that the offenders involved in the purchase of these illegal weapons are mostly criminals but also include domestic terrorists organisations operating in Northern Ireland and the Basque regions. Spapens (2007) described how defining the extent of arms trafficking in Europe is difficult due to a lack of data. However it does appear that the vast majority of arms deals are in fact legal with only 5% of arms sales being illegal. The weapons that are illegally trafficked or sold have often been legally produced and legally sold. The ways in which legal firearms cross into illegally possessed weapons are diverse but include weapons being illegally supplied directly from the factory, exports being faked, converting imitation firearms and air weapons, theft of legally owned weapons and corruption of people that are legally entitled to own firearms. The exact manifestation of the journey from legal to illegal weapons depends on many factors such as the legislation in place in any particular country and the demand for firearms. Figure 2-9 shows a model of Firearms Trafficking proposed by Spapens (2007).

Figure 2-9: Model of Firearms Trafficking



Source: Spapens (2007)

Further research on the supply and trafficking of weapons has been conducted by Wintemute et al (2004) who examined guns taken from young people in California, USA. It was concluded that the route of weapons from the point of manufacture to use in a crime is not random and can be modelled in order to target effective interventions. A substantial study was undertaken involving 2121 guns recovered from 1717 people younger than twenty-five in 1999. The findings of Wintemute et al (2004) generally support the suggestion put forward by Spapens (2007) that corrupt individuals are aiding the trafficking of legal weapons. Out of 3500 retailers in California, just ten accounted for 13.1% of weapons in the study. This showed that “a minority of retailers are disproportionately linked to crime guns” Wintemute et al (2004: 741). In 2000, the Bureau of Alcohol, Tobacco and Firearms in the United States suggested that nationwide across the USA, 1.2% of retailers were linked to 57% of guns used in crimes (ATF, 2000, as cited in Wintemute et al, 2004). The findings in both of these studies show how legal firearms are used for illegal purposes.

Wintemute et al (2004) also found that handguns purchased and used by the same person had a relatively short time to crime. This refers to the length of time between purchase of a firearm and recovery of it. Handguns recovered in this capacity had a time to crime of just 69 days compared to the median of the whole sample standing at 6.4 years suggesting that a person purchasing a gun to use personally, is likely to use it in a relatively short period after use. Wintemute et al (2004) also suggested that a time to crime of less than three years suggests deliberate gun trafficking – a statistic that is useful to note and apply elsewhere. It is important that a note of caution be applied to the findings of Wintemute et al (2004) as the legislation regarding firearms in the USA and indeed California is dramatically different to any legislation in place in Europe. Nevertheless, the findings presented provide useful evidence that patterns in firearms supply are present and can be detected.

Spapens (2007) suggested that weapons smuggling within Europe happens on a relatively small scale with smugglers only carrying a small number of weapons at any given time. However, shipments do occur regularly. This means that over time, a large number of weapons are smuggled between countries creating significant problems. Weapon trafficking also appears to be linked with the demand for firearms in any particular country.

In addition to the trafficking of legally produced guns, the supply and utilisation of illegally produced or converted weapons is also problematic. Yilmaz et al (2009) described an example of handmade weapons produced in Turkey, as a result of the demand for firearms in a particular region of Turkey and the difficulty in obtaining a licence legally there. Yilmaz et al (2009) also noted that the Black Sea region of Turkey has the highest percentage of deaths attributable to firearms in Turkey at 23%. The firearms examined and reported in this technical report were made to imitate weapons manufactured by Browning, Luger and Beretta amongst others. Yilmaz et al (2009) concluded that despite these weapons being unsafe to fire, the relative inexpensiveness of the components resulted in the widespread use of such weapons.

Once a weapon has been smuggled into a country whether legally or illegally produced, the next step is the sale of that weapon to the customer. Spapens (2007) stated that the distribution network for firearms is small and fragmented with a single firearms dealer having contacts with multiple criminal gangs. This represents the conclusion of the trafficking process and marks the beginning of firearms use in criminal events.

2.3.4 Targeting Illegally Sourced Firearms and Weapon Registration

Solutions have been suggested to deal with the problem of illegally sourced firearms. A logical way to tackle the problem is to target the firearms that start their life as legally produced weapons. Spapens (2007) suggested that all legally produced weapons need to be registered so their origin can be traced in the event that they are used illegally. Spapens (2007) also suggested that there needs to be a thorough understanding of the ways in which weapons are trafficked. This may include the types of weapons being trafficked, their origin and the trafficking routes utilised. Other measures include the educating of police officers and forensic experts to recognise firearms correctly. This would enable an understanding of the possible route the firearm may have taken and any modifications that have been made. This may provide vital intelligence. This information must then be shared between countries.

There are different ways that firearms can be registered and traced and different methods that can be utilised. Arms manufacturers keep a detailed record of all firearms that they produce. This information includes the serial number of the weapon and technical details about its construction. Manufacturers also keep records of their customers. This information can be used to trace weapons providing the number has not been deliberately removed. Interpol has one such scheme (Interpol, 2010). The problem is that much of the information used to trace firearms becomes redundant once the weapon passes into illegal hands.

One suggestion is that the ballistics information of every weapon is stored at the point of manufacture for future reference. It has been suggested that every weapon should be test fired to provide a bullet and cartridge case that can then be acquired by a ballistics analysis system[2]. This is known as a reference ballistics imaging database (RBID) as opposed to an Open Case File (OCF) with bullets and cartridge cases relating to criminal cases. There has been an increasing movement in the United States advocating this approach in response to events such as the Washington Sniper Attacks in Washington DC 2002 (Woellert, 2002). Reports have also been commissioned by government departments discussing the issues that such a database would have to overcome (Lockyer, 2003; Cork et al, 2008). As a direct result, feasibility studies have been undertaken. A detailed discussion of

[2] A discussion on ballistics analysis systems is conducted in Section 2.5 of this Chapter. A ballistics analysis system typically comprises hardware used to capture a digital representation (typically a high resolution digital image) of a bullet or cartridge case. This digital representation is then stored in a database and correlations carried out to suggest a list of potential matches to the object in question. These matches must be confirmed by a ballistics expert. Acquisition refers to the process of capturing the digital image of the object and storing it in the database.

technology used to implement these databases and the methods utilised to examine them, is conducted in section 2.5 of this Chapter but the conclusions of certain pieces of research are discussed here due to the fact that they are concerned with strategic approaches to reducing gun crime.

Tulleners (2001) examined the feasibility of a reference ballistics imaging database. The research was independently reviewed (De Kinder, 2002b) following rebuttals from the Bureau of Alcohol, Tobacco and Firearms (ATF) and Forensic Technology Inc (FTI), manufacturers of the system that was assessed (Cork et al, 2008). The work of Tulleners (2001) and De Kinder (2002b) informed the report written by Lockyer (2003). It was concluded that a reference ballistics imaging database was not feasible at the time. The reasons given were firstly that according to the independent review conducted by De Kinder (2002b), only 5% of weapons used in crimes have been legally obtained so such a database would not cover these weapons. Secondly, the cost of installing these systems on a large countrywide scale would be prohibitively expensive. Thirdly, De Kinder (2002b) suggested that the technology at the time of writing (2002) was not of sufficient quality to make correlations and searches accurate enough.

Kopel and Burnett (2003) examined the use of ballistics analysis systems to register weapons. Their conclusions supported those of Tulleners (2001) and De Kinder (2002b). Kopel and Burnett (2003) made the point that many firearms have been modified in ways that would render the ballistic signature of the weapon misleading and worthless in the context presented here. It is possible and common in some cases (for example amongst sports competitors) to routinely change the barrel, firing pin and ejector[3]. Criminals also deliberately modify components of firearms to make ballistics examinations difficult. Kopel and Burnett (2003) conducted their report on the feasibility of implementing such a database in the United States. They also point out the additional problem of registering the vast number of legally held weapons in the United States. There are 200 million firearms in circulation in the United States and registering all of these onto such a database would involve considerable time and expense. De Kinder (2002a) suggested that one compromise would be to test fire legally held weapons and then transfer these test fires to the open case file in the event of loss or theft. It may be the case that there are ways that future technology can assist with this problem.

The next section examines how policing strategies can affect the success of investigations where crimes involving firearms have been committed.

[3] An explanation of the different components of firearms and their significance for identifying bullets and cartridge cases fired from the same gun is conducted in Section 2.5 of this Chapter.

2.4 - Investigating Gun Crime I – Investigative Process

2.4.1 Specialist Police Operations – Operation Trident

There are many approaches to tackling crimes involving firearms. These include policing initiatives, policy changes and the utilisation of technology, but are quite difficult to assess for efficacy (Sherman, 2001; Squires, 2008). Smith et al (2010) showed that the majority of crimes involving firearms in the UK are committed in London, Manchester and Birmingham. This has led to specific police interventions being put in place to target these areas. Crimes involving firearms in London are generally investigated by a specialist operational command unit (OCU) known as Operation Trident. This operation was set up to tackle the specific problem of shootings, murders and injuries committed by and against the young, black community in London. According to statistics presented by Operation Trident, 75% of shootings that occur in London involve the victim and suspect coming from the black community. Operation Trident involves other agencies and initiatives to tackle gun crime as well as dedicated policing (Metropolitan Police, 2010).

The impact of Operation Trident and the implications of such an approach to tackling firearms offences in the UK have been studied and discussed at length by Roberts and Innes (2009). The authors describe how Operation Trident follows a suppress and manage strategy to tackle gun crime and not only aims to improve the way in which shootings are investigated but also to improve the detection rate of such offences. The remit of Operation Trident has also widened to include strategic interventions that aim to disrupt the supply of weapons. The impact of Operation Trident can be considered in different ways. Firstly detections and convictions have improved through the implementation of Operation Trident. However, if the number of firearms incidents, number of attempted murders and the number of actual murders is considered a different picture emerges (Roberts and Innes, 2009). For the period 2000 – 2005 the murder rate in the black community actually remained relatively constant suggesting that despite improved detection rates, the actual level of offending had not changed. This has led to Operation Trident widening to include social interventions such as media campaigns and educating young children about gun crime to try and steer them away from becoming involved in criminal activity (Roberts and Innes, 2009).

Roberts and Innes (2009) suggested that while the approach taken to tackling gun crime such as that by Operation Trident has advantages it also has other effects that need to be understood. Operation Trident has created a specific level of expertise about dealing with a particular type of crime. Roberts and Innes (2009) rightly pointed out that the eventual use of firearms is driven by a complex set of issues and distinct events in the lives of individuals. A concern is expressed that there is not a thorough understanding of these issues and that because community and emergency tasks are handled by less specialised teams, the ability to gather vital intelligence is being lost. In this research Roberts and Innes (2009) presented the example of Operation Trident as symptomatic of a wider shift in the roles of police officers in the UK .They argued that there is no longer a generalist police constable that is engaged with the community and is in a position to gain useful intelligence. Instead policing tasks are split into specialist units with officers specialising in that particular domain. Roberts and Innes (2009) argued that while improvements have been made to detection rates and the way in which gun crime is investigated, the increased specialisation that is occurring in the police is resulting in intelligence gaps. They also suggested that further research should be conducted to assess the effects of such organisational restructures. In addition, gun crime events that are gang related are often difficult to investigate because witnesses are reluctant to come forward to testify and there is reluctance on behalf of the victim to report the full circumstances of a crime to the police. This has led to suggestions that witness protection schemes should be improved (Squires, 2009).

2.4.2 Specialist Police Operations – Operation Ceasefire

Krug et al (1998) concluded that the United States had the highest rate of gun fatalities. Many interventions have been implemented in the USA. One of the most successful was Operation Ceasefire. This started in Boston as a result of exceptionally high gun deaths amongst young people in the 1980’s and 1990’s and is an example of an evidence based policing approach described by Bullock and Tilley (2009: 381) as “the application of measures on the basis of robust evidence of their effectiveness”. Kennedy, Braga and Piehl (2001) explained how the homicide rate for youths in Boston rose 418% between 1984 and 1994 and the rise was mainly attributed to the drugs market and related gang activity. Operation Ceasefire was a problem orientated policing approach, that involved a partnership between academics and practitioners and focussed on two specific areas. The first was illegal firearms trafficking (supply) and the second was the fear created by the illegal drugs market that resulted in many young people carrying guns for protection (demand). Kennedy, Braga and Piehl (2001) explained how a working group was formed comprised of local agencies and community leaders that recognised the problems facing Boston. The first action to tackle gun trafficking was to build a case against and prosecute a known gun dealer supplying new weapons. This action alone resulted in shootings being almost totally stopped temporarily because the main supply of new firearms that had never been used before was halted. The second focal point of Operation Ceasefire was to reduce the fear amongst youths that resulted in gun carrying. To achieve this, research was carried out to find out the exact nature of the problem in Boston and characteristics of the people involved in the murders. The finding was that the vast majority of both victims and offenders had extensive criminal backgrounds. The number of gangs and the areas where they were operating was estimated. Kennedy, Braga and Piehl (2001) found that there were 1,300 offenders operating in 61 different gangs and that 60% of homicides were gang related but not because of drug markets or turf wars. Instead most of the homicides were caused by disputes, sometimes relatively trivial, between gangs.

Alongside the work being carried out to disrupt the supply of guns, interventions specific to gangs were carried out. If there was a dispute between two gangs that was causing violence, those gangs would be focussed on. Many gang members were on probation for other offences so they were prosecuted for this. Also many gang members were committing minor offences such as driving without a licence or insurance. These offences were also focussed upon and it soon became apparent that the gangs would not be left alone until the violence stopped. This message was communicated effectively by the police to key gang members. Once this approach was shown to work, it was implemented as policy. Kennedy, Braga and Piehl (2001) concluded that the problem orientated policing approach that focussed on supply and demand was at least partly successful in reducing gun violence. They acknowledged a crucial element was the involvement of local practitioners and the creation of a working group that understood the exact aims and objectives of the operation.

Braga et al (2001) examined the impact of Operation Ceasefire on gun crime in Boston using police data and found a 65% decrease in the monthly number of youth homicides and a 32% decrease in the monthly number of calls to police reporting shots fired. Braga et al (2001) conducted statistical analyses and concluded that the Operation Ceasefire interventions were significantly associated with these reductions. Braga et al (2001) concluded that the activities carried out by Operation Ceasefire were successful because they introduced a strong deterrent and that interventions were specifically targeted at those gangs engaged in violence at a particular time rather than targeting all gangs. The approach to tackling gun crime in Boston has been recognised as one of "the best examples [of problem oriented policing] we have so far" (Tilley 2010: 192). Braga et al (2001) argued that this focussed approach can be transferred to other cities where there is a problem with guns and gang violence. The Operation Ceasefire approach has been transferred to Los Angeles with some success (Gonzales, Henke and Hart, 2005). Aspects of the approach have also been transferred to Manchester in the UK (Bullock and Tilley, 2008).

The review of the literature has focussed on the criminological issues surrounding gun crime. The prevalence of crimes involving firearms in the UK and other countries has been discussed. Factors that influence an individual's involvement in gun crime have also been discussed along with preventative strategies from legislative and policing perspectives. Forensic science plays an increasingly important role in the investigation of many crimes. The investigation of crimes involving firearms often involves forensic examination of bullets, cartridge cases and weapons. The next section of the Thesis discusses the forensic examination of such exhibits and the processes and technologies used in the laboratory.

2.5 - Investigating Gun Crime II – Forensic Ballistics Analysis and Implications for Technology

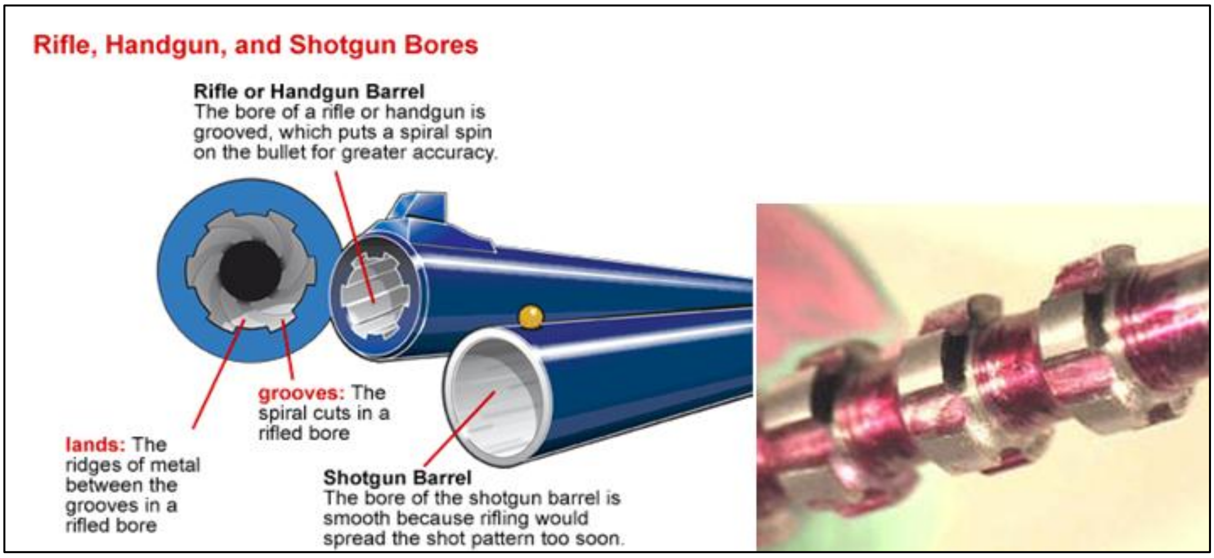
Crimes involving firearms often produce bullets, cartridge cases and weapons that upon examination can provide intelligence or evidence. This can be vital to the successful detection and prosecution of gun crimes. It is critical that the evidence gathering process and the techniques utilised yield as much intelligence and evidence as possible. This section discusses issues relevant to the forensic examination of ballistics exhibits.

The exact origin of forensic ballistics examinations is unknown (Heard, 2008). However, there is a large quantity of literature that has been published in the past sixty years that attempts to explain the scientific principles upon which ballistics examinations are based (Nichols, 1997; Nichols 2003; Nichols, 2007). The scientific principles of ballistics analysis have been challenged (Schwarz, 2004; Schwarz 2007; Edwards, Gatsonis and Kafadar, 2009) as have the scientific principles behind other disciplines of forensic science (Daubert v. Merrell Dow Pharmaceuticals, Inc. (1993) 509 U.S. 579, 589). One of the reasons behind this debate is the fact that forensic ballistics is a complex discipline and statements about the absolute certainty of matches cannot be made (Bunch, 2000). The analysis of bullets and cartridge cases with the aim of matching exhibits together is inherently subjective and this has led to continued debate around the scientific process and standards that could or should be developed to make the process more rigorous (Bunch, 2000; Song et al 2009; Chumbley, et al, 2010; Saks, 2010). The impact of this debate on evidence presented has also been discussed (Kaasa et al, 2007). An overview of the general principles is presented in this Chapter.

2.5.1 Matching Bullets

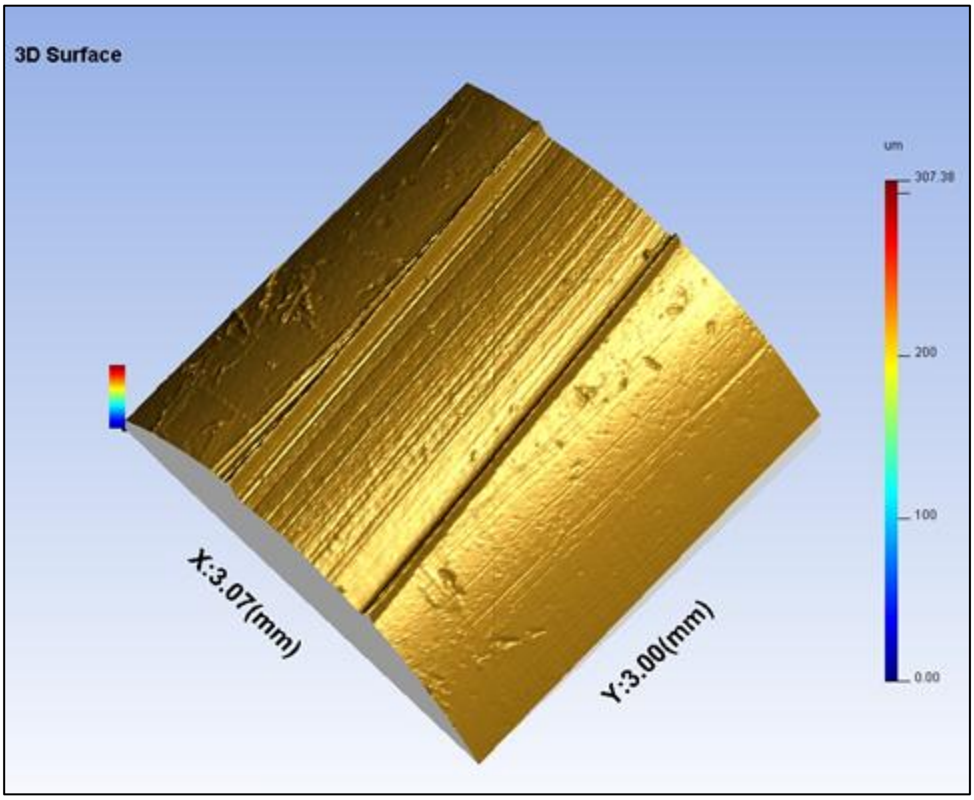
Striations that are imprinted onto bullets as they are fired through the barrel of a gun are left because of the rifling that is cut using a boring tool into the barrel inner surface. The rifling in the barrel consists of grooves in a spiral or helical form on the inside of the barrel. The rifling causes the bullet to spin stabilising the trajectory of the bullet to ensure the gun is fired with the required accuracy. Heard (2008) explained how the rifling consists of lands and grooves. Grooves are depressions in the barrel cut away by the boring tool used to rifle the barrel. Lands are the sections of the barrel that are not machined directly by the boring tool which generates the rifling. The length of the barrel needed to complete one spiral is called the twist and the degree of twist is critical in stabilising the bullet. Rifling can be left twist or right twist and the number of grooves cut into the barrel can vary between one and twenty four. The number of grooves and the angle are indicative of a particular manufacturer. The characteristics are known as class characteristics. Detailed forensic examination of bullets is concerned with the striations left on the bullet as a result of the physical interaction of the soft bullet with the harder rifling of the barrel. In particular, the imperfections in the rifling that result from the boring process are imprinted onto the bullet surface. It is these imperfections said to be unique to each weapon that are used for identifications. These are known as individual characteristics and are different to class characteristics[4]. Figure 2-11 shows a section of a bullet and the striations can be clearly seen.

Figure 2-10: a) Rifling in Gun Barrels b) Barrel Boring Tool giving Square Rifling Grooves



[4] Class characteristics whether concerning bullets and cartridge cases refer to the characteristic markings imprinted by a particular make and / or model of weapon. They can be used to determine the type of weapon that fired the bullet or cartridge case. Class characteristics can be used to narrow down the number of potential weapons that may have fired the bullet or cartridge case. Individual characteristics refer to the markings that identify the specific weapon that fired the bullet or cartridge case.

Figure 2-11: A Section of a Bullet Showing Striations across a Single Groove



Class characteristics can identify the make and model of the weapon used to fire a bullet. Examples of class characteristics are the number of lands and grooves, the angle of twist and the direction of the twist. There are many databases in operation that record details of these class characteristics and enable searches to be performed by ballistics examiners who can identify the family of weapons that a gun is likely to have come from.

Barrels can be rifled using a variety of different tools and methods and these all have an impact on the nature and quality of striations imprinted on bullets. Rifling also consists of different shapes and again these shapes have an impact on the quality of marks left of bullets. Heard (2008) stated that the majority of modern rifling is either square or polygonal. Polygonal rifling has no sharp edges and as a consequence can result in difficulties in matching bullets fired from polygonal rifled weapons.

2.5.2 Matching Cartridge Cases

The main components of a firearm that create impressions on a cartridge cases are the firing pin, the breech face, the ejector and the extractor. The firing impression is caused by the firing pin striking the cartridge case and igniting the primer. As the weapon is fired, the cartridge case strikes the back of the weapon (the breech face) and causes an imprint of the breech face to be left on the relatively softer cartridge case head. Figure 2-12 shows a cartridge case head and Figure 2-13 shows a cartridge case head with the firing pin and breech face marked. The extractor marks and ejector marks are caused by the mechanism in the weapon that removes the cartridge case from the chamber. These are typically only found in automatic, semi-automatic and self-loading weapons. Revolvers require a person to manually open the weapon and remove the spent cartridge cases. As was the case with bullets, markings on cartridge cases will consists of class characteristics and individual characteristics. An example of a class characteristic is a rectangular firing pin impression which is only found on ammunition fired from a Glock weapon (Figure 2-14). Individual characteristics are caused by imperfections in the manufacturing process of components of firearms and it is commonly accepted that these can be used to match two or more objects together.

Figure 2-12: Cartridge Case Head

Figure 2-13: Cartridge Case Head with Breech Face Impression (Left) and Firing Pin Impression (Right)

Figure 2-14: A Cartridge Case Head Showing the Class Characteristic of a Rectangular Firing Pin only Produced by Glock Weapons

2.5.3 Ballistics Analysis in the Past – Comparison Microscopy

The comparison optical microscope is still the instrument of choice for laboratories conducting ballistics examinations. Evidence presented in court will be in the form of an examination conducted using optical microscopy. The procedure for matching bullets and cartridge cases using microscopy will vary between countries but a general overview is presented by Heard (2008). The first issue that must be overcome is accidental agreement – the striations that match but only by chance. To overcome this, a known non-matching bullet will be compared with the case bullet to see if there are any accidental matching striations that should be discounted. The merits of this step in the procedure are arguable as this known non-matching object has no relevance to the test fire. After this, a series of test fires will be obtained from the suspect weapon and attempts made to match the striations to the case bullet. If an examiner finds a potential match, it will be confirmed by another examiner. The above process also applies to cartridge cases.

It is important to note that different variables will impact the quality of marks imprinted on cartridge cases and bullets. In addition, the marks imprinted will change every time the weapon is fired. The variability in striations on bullets and cartridge cases can vary from small to large depending on the number of times the weapon has been fired between the firing of the suspect object[5] and the object it is being compared with. De Kinder (2002a) identified factors such as the metal type used for the chamber (hardness) and breech face (hardness) and the metal type of the bullets fired through a barrel (hardness) as being particularly influential in affecting the striations imprinted on bullets. With regards to cartridge cases, the firing pin impressions, ejector and extractor marks are likely to vary over time. This variability obviously impacts the success or failure of microscopic examinations. De Kinder (2002a) suggested that relatively soft lead bullets deposit metal in the barrel and after around fifty firings, the striations on the bullet will have changed so much that identification becomes impossible. Other environmental factors such as the decomposition of a body can also affect the quality of marks left on bullets (Smith et al, 1993).

2.5.4 Declaring a Match – Confirmation Bias

The issue of confirmation bias is frequently studied in Psychology but research in the forensic ballistics discipline is less prevalent. Confirmation bias occurs when evidence is gathered and analysed to fit an existing hypothesis or belief and is especially dangerous in law enforcement because it can lead to vital pieces of evidence being overlooked or their importance exaggerated. When comparing ballistic objects such as cartridge cases and bullets, confirmation bias has the potential to threaten the objectivity of the examiner and affect the outcome of a criminal case.

[5] "Object" is used to refer to a cartridge case or a bullet. The term is used when a point is being made that applies to both bullets and cartridge cases. It is important to note that bullets and cartridge cases are always stored in different databases and a bullet will never be correlated against a cartridge case and vice versa.

Risinger et al (2002) explained four ways in which confirmation bias can be manifested. Firstly, more information than is necessary can be provided to the examiner. Secondly, examiners may talk to each other about the case in question undermining independent evaluation of the work. Thirdly, information that is received after the examination may prompt the examiner to repeat the examination and alter the conclusions drawn. Finally, the police or another stakeholder in the case may not be satisfied with the conclusions drawn and may request a re-examination. At the same time they may communicate their expectations of the re-examination biasing an examiner.

Kerstholt et al (2010) conducted experimental research to ascertain the vulnerability of firearms examiners to confirmation bias. Six firearms examiners were given sets of bullets accompanied by information that might bias them towards a particular conclusion or accompanied by neutral information. This information took the form of a report that usually accompanies evidence when submitted to the laboratory. The biased information consisted of a description of the crime that stated that only one suspect and one gun were involved yet two bullets were recovered from the victim – suggesting that the bullets should match. The second, neutral information consisted of a description of the crime that stated that two bullets were recovered, two suspects were seen and two guns were fired meaning that there was no expectation of whether or not the bullets should or should not match. Kerstholt et al (2010) found that the examiners did not appear to be affected by confirmation bias and that the information contained in the report did not affect the conclusions of the examiners. There are a number of explanations for this result. Firstly, and the most obvious is that confirmation bias did not exist amongst this group of firearms examiners. Another possible explanation is the small sample size (only six examiners) meant that any observed effects would need to be large to result in a statistically significant difference. The examiners were also aware that they were participating in an experiment and that the case was not real.

Assuming that confirmation bias was not present amongst this group, Kerstholt et al (2010) suggested reasons why this is not the case. It was suggested that forensic examiners are actually quite critical and sceptical of any information about the case that is presented to them and therefore disregard it when undertaking an examination. Burns (2001) suggested that examiners are aware that they may be accused of being biased and suggests three concepts to tackle this. Firstly, answering questions regarding the examination and related processes honestly. Secondly, being very conscientious of how an examiner presents evidence in court to ensure it is understood by the jury and thirdly always keeping an open mind and letting the evidence speak for itself. While these concepts may be somewhat vague in practise they do demonstrate that examiners have some awareness of the issue of bias.

Although the findings of Kerstholt et al (2010) are interesting and somewhat reassuring, there are some methodological issues which may account for the findings. Firstly, there was not a control condition. Recall that there was biased and neutral information presented to the examiners. A control condition could have been included that would have involved presenting the bullets to the examiners without any information whatsoever. Secondly, this study was conducted in the Netherlands. The findings should be applied with caution to other examiners in other countries because there may be elements in the training methods utilised by the Netherlands Forensic Institute that are country specific and do not apply in other countries.

2.5.5 Ballistics Analysis Present – Ballistics Analysis Systems Manufactured by Forensic Technology

Computer aided methods have been developed and are being increasingly used to assist with the task of conducting ballistics examinations and matching ballistics exhibits to weapons. Ballistics analysis systems typically work by acquiring a digital image of the bullet or cartridge case, utilising algorithms to extract a digital signature of the key features of the bullet or cartridge case from the image and then submitting the image and digital signature to a database. Correlation algorithms are then run across the database and the user of a ballistics analysis system is presented with a ranked list of potential matches. A ballistics expert will then examine these potential matches in the hope of finding a match. These systems are designed to link crimes together that otherwise would not be linked but are often used in other ways such as an audit tool[6] for bullets and cartridge cases. It has also been suggested that this technology could be used to capture and store digital signatures from legally held weapons. This is known as a reference ballistics imaging database rather than an open case file where bullets and cartridge cases relating to crimes are stored.

Research conducted on ballistics analysis systems[7] appears to be split into two categories. The first concerns the performance of the systems given the parameters of a test set of ammunition (Tulleners 2001; De Kinder, Tulleners and Thiebaut 2004; George 2004a; George 2004b; Nennsteil and Rahm 2006a; Nennsteil and Rahm 2006b). The second category consists of research into the

---

[6] Use as an audit tool refers to the practise of using a ballistics analysis system to acquire and store digital images of bullets and cartridges. The primary focus is on the storage and retrieval of the bullets and cartridge cases through case reference numbers and exhibit reference numbers. The correlation capability is perhaps of secondary importance in this context.

[7] For the purposes of this Thesis a "ballistics analysis system" is defined as the hardware and database needed to acquire and correlate a sample of bullets or cartridge cases. The exact configurations of ballistics analysis systems do vary. For example, some laboratories will use a single standalone system consisting of an acquisition station to acquire cartridge cases and bullets and the database where images and representations of these objects are stored. Others will have a networked system where multiple acquisition stations all connect to a single database. In this Thesis unless described otherwise, a "ballistics analysis system" refers to a standalone system.

usability of the ballistics analysis systems and working practises that affect performance (Chan, 2000; Argaman, Shoshani and Hocherman, 2001; Koffman and Silverwater, 2001).

Ballistics analysis systems began to be developed in the early 1990s by a company called Forensic Technology Inc (FTI) which now has a large market share. Ninety five percent of all ballistics analysis systems globally are manufactured by FTI. These products are the Integrated Ballistics Identification System (subsequently referred to as "IBIS") suite of products. The most recent version of the technology is the IBIS Trax 3D (BulletTRAX and BrassTRAX 3D) systems. The previous incarnation of the technology is called IBIS Heritage. Other companies have developed competing products and some of these systems are installed in countries around the world. Due to the high cost of these systems and the procurement rules in place for public sector organisations, a number of studies have been conducted to assess the functionality, performance and cost effectiveness of these systems. A review into ballistics analysis systems with particular reference to the IBIS Heritage system in the USA was conducted in 2008 by the National Academy of Science (Cork et al, 2008). The research described here is also summarised in that report. The conclusions of that report are described at the end of this section.

This section discusses previous work that has been conducted assessing and comparing ballistics analysis systems. The different systems in operation have strengths and weaknesses and there are many different types of methodology that can be implemented. These methodologies have to take into account the many variables that are present in forensic ballistics. The main variable that affects performance of a system is whether it is acquiring and correlating a cartridge case or a bullet. The nature of the two types of object and the impressions imprinted on them are radically different. Consequently different data acquisition and correlation techniques are utilised. The ability of ballistics identification technologies to acquire and correlate cartridge cases has been examined at a greater frequency and in more detail than the ability of these systems to acquire and correlate bullets. Brinck (2008) suggests that this is because cartridge cases, whilst being three dimensional objects, have characteristic markings that are easier to acquire and identify from a two dimensional digital image. Bullets however are truly three dimensional as are the markings that identify the weapon that fired them.

The performance of ballistics analysis systems has also been assessed for the purposes of gun registration. It has been proposed that every gun that is legally sold should be test fired and the cartridge cases and bullets entered into a system such as IBIS Heritage. This would enable the database to be checked when necessary. Such a database would be considerably large therefore research has been conducted to assess the feasibility of such as scheme (Tulleners, 2001; De Kinder, 2002a; De Kinder, 2002b; De Kinder, Tulleners and Thiebaut, 2004; Cork et al, 2008). A prerequisite to the application of such as registration scheme would be a guaranteed, extremely high success rate in correlation matching.

In 2001 a feasibility study was commissioned by the California Department of Justice to evaluate the ability of the IBIS Heritage system to underpin a reference ballistics imaging database. The review was conducted by Tulleners (2001) and took the form of a technical evaluation of IBIS Heritage. As part of the review, eight performance tests were devised. The most relevant to this Thesis is "Performance Test 1" (Tulleners, 2001: 8-1). This involved a background sample[8] of 792 cartridge cases fired from Smith and Weston 4006 pistols. The ammunition calibre was .40 and of Federal type. Fifty cartridge cases also of type Federal were selected to be correlated against the database. IBIS Heritage provides different correlation lists for the breech face algorithm and firing pin algorithm and the results showed that for the breech face algorithm, IBIS Heritage correlated 38% of the test cartridge cases in the top ten positions. For the firing pin algorithm, the percentage of matches correlated in the top ten was slightly higher at 42%[9]. Tulleners (2001) also investigated the effect of different ammunition types, correlating a test set of 72 cartridge cases of different ammunition type against the 792 Federal cartridge cases. The results showed that IBIS Heritage correlated the matching cartridge cases in the top ten on 18% of occasions for both the firing Pin and breech face algorithms. Tulleners (2001: 1-1) concluded that the application of IBIS Heritage to capture cartridge cases for all legally held weapons was not suitable as "the number of cartridge cases will be so large as to be impractical and will likely create complications so great they cannot be effectively addressed".

The technical review conducted by Tulleners (2001) was followed by De Kinder (2002b) in the form of an independent review because of rebuttals of the original research issued by FTI and the Bureau of Alcohol, Tobacco and Firearms (ATF). The criticisms of Tulleners (2001) by the ATF concerned the choice of Federal ammunition. The ATF argued that the ammunition type was too hard, skewed the results and that Remington-Peters ammunition should have been used instead. De Kinder (2002b) rejected this argument citing the fact that Remington-Peters ammunition is actually harder than

---

[8] A background sample refers to the objects in the database that create the "noise". A system performing correlations would have to search against and discount all of the objects in the background sample. The test sample usually consists of pairs or set of objects. The matching object or objects to the questioned object will be mixed in with the background database. The system will search against the background set (non-matching objects) and the matches to distinguish the true matching objects.

[9] Results of this nature can also be referred to as the "success rate". Success rate for the purposes of this Thesis is defined as the percentage of occasions where an object was correlated on a correlation list of a specified length.

Federal ammunition. FTI objected to the fact that eight out of the 50 test Federal cartridge cases could not be matched manually by one of their firearms examiners. They sought to have these eight cartridge cases removed from the sample which would have improved the percentage success rates reported by Tulleners (2001). De Kinder (2002b) also rejected this argument describing it as “unacceptable” (De Kinder, 2002b: 4), stating that the use of ballistics imaging technology should not be restricted to cartridge cases that can be matched by a human examiner.

De Kinder, Tulleners and Thiebaut (2004) subsequently conducted a study to examine the feasibility of a reference ballistics imaging database. The study was conducted with a large sample of objects comprising of cartridge cases generated by firing 600 Sig Sauer pistols. Each pistol was fired twice with Remington ammunition. One of these cartridge cases was entered into the database. Each pistol was then fired an additional five times with five different brands of ammunition. Cartridge cases from the second set of test fires were then randomly selected to be correlated against the database. Tests were performed correlating cartridge cases of the same ammunition type and of different ammunition types. Thirty two Remington test fires were selected and correlated against the database which contained ammunition from the 600 guns. For the breech face algorithm, 53.12% of samples were correlated in the top ten. For the firing pin algorithm the percentage found in the top ten was 43.75%. For both algorithms combined, 71.8% of cartridge cases were found in the top ten on the correlation list. To test the functionality of IBIS Heritage with different brands of ammunition, 160 samples equally distributed amongst the five ammunition types, were selected from the second round of test fires. The results showed that the success of IBIS Heritage varied between 6% and 37.5% of the known matches appearing in the top ten on the correlation list depending on the specific ammunition type. The overall success rate (top ten) for the breech face algorithm was 10%. The percentage success rate overall (top ten) for the firing pin algorithm was 14.38%. The combined overall success rate for the breech face and firing pin algorithms was 21%. The performance of the database and correlation results were also assessed as the database increased in size. This demonstrated that the range of ranking positions of known matches in the database increased as the database size increased.

De Kinder, Tulleners and Thiebaut (2004: 215) conclude that implementing a database for the purpose of gun registration is “unsuitable for law enforcement” and that such a database has “inherent failings”. The reasons given are firstly the fact that performance decreases significantly when different brands of ammunition are used. Secondly, the authors highlight the fact that the success rates quoted in their research were achieved with a database containing images from only 600 pistols. If such a database was to be implemented the number of weapons stored in it would be significantly greater in the region of millions. Thirdly, De Kinder, Tulleners and Thiebaut (2004) also observed that the performance of the IBIS Heritage system decreased as the database grew larger providing the rationale for their recommendation. As a reference ballistics imaging database is deemed unsuitable, it is suggested that alternative methods for firearm registration are considered. An example would be micro-stamping firearms during the manufacturing process. This involves micro engraving distinguishing marks or a serial number onto a suitable area of the weapon that can be used for identification later if necessary. This was also recommended by Cork et al (2008).

George (2004a) also evaluated the performance of IBIS Heritage when correlating cartridge cases and used 500 Smith and Weston 0.40 calibre pistols to generate the background sample of cartridge cases using Federal and Remington ammunition. George (2004a) concluded that when correlating Federal ammunition with Federal ammunition the success rate (top ten) was 72%. When correlating Remington with Remington the success rate was 48% and when correlating different brands of ammunition (Remington to Federal or vice versa) the success rate dropped to 11%. This supports the findings of Tulleners (2001) and De Kinder, Tulleners and Thiebaut (2004). Using these results George (2004a: 288) concludes that “the equipment fails to achieve the expectations promoted by Forensic Technology”. Whilst it is noted that the performance of IBIS Heritage decreases when different ammunition is correlated, George (2004a: 288) states: “Criminals do not feel obligated to use the ammunition our laboratory equipment may prefer”. This led to follow up research utilising cartridge cases of different ammunition types. George (2004b) extended the database to contain 850 cartridge cases generated by firing 540 Smith and Weston 0.40 calibre pistols. The ammunition brands in this study were Federal, Winchester and Remington. George (2004b) selected twenty five weapons as the test sample and performed correlations with three cartridge cases per weapon (one for each brand). Each weapon had in total six cartridge cases in the database. The correlation list positions of the other five matching cartridge cases were recorded and the success rate was 25%. George (2004b) considered the application of the IBIS Heritage technology to a reference ballistics imaging database and concurred with Tulleners (2001) and De Kinder, Tulleners and Thiebaut (2004) that “more work needs to be done before Ballistics Fingerprinting can be considered feasible” (George, 2004b: 295).

Nennsteil and Rahm (2006a) examined the IBIS Heritage system in detail. They considered the variables that affect the success and failure rate and the results generated. They then applied the variables to prior research conducted by Tulleners (2001), De Kinder, Tulleners and Thiebaut (2004) and George (2004b). Success in this paper is defined as “the probability that an existing match could actually be found by the correlator” (Nennsteil and Rahm, 2006a: 18). If the success rate is determined by the system finding a match then this term also has to be defined. As previously noted IBIS Heritage produces a correlation list of possible matches and a firearms examiner then has to examine the list and then the objects to declare a match. Therefore the appearance of the object on the correlation list of predetermined length determines the success rate. The error rate or failure is defined as a known match appearing outside the correlation list of a particular length.

Nennsteil and Rahm (2006a) defined five variables that affect the success and failure rate of the IBIS Heritage system. The first is the type of mark on the object. Different markings on the same object can be evaluated by the IBIS Heritage system independently. The different types of marks on cartridge cases are the breech face (BF), firing pin (FP) and ejector mark (EM). An explanation of these marks was explained at the start of this section. On bullets the mark types are the max phase (MP). This is the highest score generated during the correlation of all the land impressions. The peak phase (PP) is the highest score generated from the comparison of the individual land impressions within the max phase. The third mark type for bullets is the max lea (ML). This is the highest score generated from the comparison of individual land impressions.

The second variable defined by Nennsteil and Rahm (2006a) is the quality of the marks available on the object. The type of ammunition and the age of the firearm are just two variables that can affect the quality of marks on cartridge cases and bullets. The third variable defined by Nennsteil and Rahm (2006a) is the size of the database. This variable refers to the number of objects that will be compared to the object in question. The IBIS Heritage system only compares objects that are of the same calibre. For example, a database might contain 1000 objects. The object in question is 9mm and the database contains 500 9mm objects. Therefore the database size in this case, as defined by Nennsteil and Rahm (2006a) would be 500.

The fourth variable is the number of signatures from a particular mark type to be examined, that have come from the same source (firearm). This number depends on the number of times a gun has been test fired or the number of objects recovered at a crime scene. For example, a gun that is test fired twice would produce two cartridge cases, resulting in two signatures from the same source. The number of objects entered onto the IBIS Heritage system varies between countries. Argaman, Shoshani and Hocherman (2001) suggested that although most operators only enter one cartridge case per weapon, Israel enter two and find that despite the increased workload, results are better. Argaman, Shoshani and Hocherman (2001) suggested that the two cartridge cases should be as different as possible.

The fifth variable described by Nennsteil and Rahm (2006a) is the number of objects on the correlation list that will be examined by the operator or ballistics expert. There are no standards in place to determine the length of the correlation list. The number of potential matches returned by the system and examined, varies between countries and laboratories. The IBIS Heritage training manual suggests that the list should be ten objects in length whilst other researchers such as

Silverwater and Koffman (2000) have suggested that the correlation list should only contain five objects. Other researchers such as Brinck (2008) have considered the top twenty positions. Clearly when assessing the performance of a system, the correlation list length is directly related to the measure of success. The chance of a system finding a match is directly related to the length of the correlation list. The definition of correlation list is also interchangeable because the IBIS Heritage system produce different correlation lists for the different identifying marks on a cartridge case head. For example, a list is produced for the firing pin impression and another is produced for the breech face impression.

Nennsteil and Rahm (2006a) discussed each variable in detail and the implications for the results that are generated by IBIS Heritage. The quality of marks on a ballistics object appeared to affect the success of correlation. The recommendation made was that test fires should be conducted using the same brand of ammunition as the evidential object seized at the crime scene. This supports the findings of De Kinder, Tulleners and Thiebaut (2004). Nennsteil and Rahm (2006a) also found that IBIS Heritage performed best when all available markings were taken into account rather than just a single type of mark. It was also stated that multiple test fires should be uploaded into the database and wherever possible multiple evidential samples supporting the experiences of Argaman, Shoshani and Hocherman (2001). In terms of the correlation list generated, the authors suggested that this should contain between five and ten objects. They suggested that increasing the correlation list length (and the resultant workload of the examiner) does not produce a worthwhile increase in performance.

Nennsteil and Rahm (2006a) found that the success rate of IBIS Heritage decreased as the database size increased. This supports the findings of earlier research conducted by De Kinder, Tulleners and Thiebaut (2004). This is not surprising as the number of correlations performed increases as the number of objects in the database increases. Nennsteil and Rahm (2006a) suggested that it is practical to try and keep the database size small to increase the performance of IBIS Heritage. This however may become problematic as the number of objects seized from crime scenes cannot be controlled and it has been suggested that test fires using different types of ammunition should be uploaded (Argaman, Shoshani and Hocherman, 2001). This fact was recognised as contradictory by Nennsteil and Rahm (2006a). If there are a large amount of open cases that need to be checked against a particular object, then the checks should be able to be performed. Perhaps an implication of the research of Nennsteil and Rahm (2006a) is that the onus is on the ballistics examiners to lobby the technology manufacturers to improve and optimise correlation algorithms. It was also suggested that after a period of time, certain exhibits should be removed from the database. This may prove problematic as removing these items may actually obscure links between crimes and result in crimes remaining undetected.

The authors, (Nennsteil and Rahm, 2006a) followed up their research by assessing the performance of IBIS Heritage using a realistically created database (Nennsteil and Rahm, 2006b). They noted that previous work had not assessed the performance of IBIS Heritage with a database of objects that would represent a real open case file. Nennsteil and Rahm (2006b) suggested that a realistic dataset representing an open case file should contain ballistics objects of different ammunition types from weapons of different calibres, makes and models. Using the parameters defined in their earlier work, Nennsteil and Rahm (2006b) quoted a success rate of 75% - 95% for cartridge cases and 50% - 75% for bullets showing that IBIS Heritage was less effective for bullet comparisons (Nennsteil and Rahm, 2006b). Table 2-2, Table 2-3 and Table 2-4 summarise the success rates of research that has been conducted examining the performance of IBIS Heritage when correlating cartridge cases.

Table 2-2: Breech Face Algorithm Success Rates (Top 10)

Author (s)	**Ammunition**	**Success Rate (Top 10)**
Tulleners (2001)	Same ammunition	38%
Tulleners (2001)	Different ammunition	18%
De Kinder, Tulleners and Thiebaut (2004)	Same ammunition	53.12%
De Kinder, Tulleners and Thiebaut (2004)	Different ammunition	10%

Table 2-3: Firing Pin Algorithm Success Rates (Top 10)

Author	**Ammunition**	**Success Rate (Top 10)**
Tulleners (2001)	Same ammunition	42%
Tulleners (2001)	Different ammunition	18%
De Kinder, Tulleners and Thiebaut (2004)	Same ammunition	43.75%
De Kinder, Tulleners and Thiebaut (2004)	Different ammunition	14.38%

Table 2-4: Combined Algorithm Success Rates (Top 10)

Author	**Ammunition**	**Success Rate (Top 10)**
De Kinder, Tulleners and Thiebaut (2004)	Same ammunition	71.8%
De Kinder, Tulleners and Thiebaut (2004)	Different ammunition	21%
George (2004a)	Same ammunition (Federal)	72%
George (2004a)	Same ammunition (Remington)	48%
George (2004a)	Different ammunition	11%
George (2004b)	Different ammunition	25%
Nennsteil and Rahm (2006b)	Ammunition not specified	75%-95%

Research by Tulleners (2001), De Kinder, Tulleners and Thiebaut (2004) and George (2004a) and George (2004b) has evaluated the performance of IBIS Heritage when correlating cartridge cases. Brinck (2008) examined bullet performance comparing the IBIS Heritage system with the latest version of the IBIS technology called BulletTRAX-3D. Brinck (2008) used bullets fired through ten consecutively manufactured barrels and examined each systems capabilities with bullets only. The individual differences in striations imprinted on bullets are caused by the barrel manufacturing process. Because consecutively manufactured barrels are produced consecutively, theoretically the differences between them should be smaller. There should be minimal differences in the wear of the components used to manufacture the barrels and consequently the differences in the imprinted striations on bullets should be minimal.

The aim of Brinck (2008) was to identify the abilities of each ballistics analysis system to correctly identify a match and to examine the correlation list to see where the object of interest appeared and what other objects were suggested by the system as being of interest. The study aimed to ascertain if the 3D ballistics analysis system (BulletTRAX 3D) was better at identifying bullets than the preceding two dimensional technology (IBIS Heritage). Brinck (2008) pointed out that this issue is of crucial importance to any laboratory wishing to procure new equipment.

The model of firearm used by Brinck (2008) to act as a test sample was a P10-45 semi-automatic pistol with the trade name “Warthog”. This weapon is a 45 calibre pistol and the characteristics of it are that is has six lands and grooves and a left hand twist. The land and groove widths are 0.07 and 0.157 inches respectively (Brinck, 2008). The sample used in Brinck’s research came directly from the manufacturer with the assurances that each component was manufactured consecutively. Ideally, this process would have been witnessed by the researcher to ensure the components had been manufactured consecutively but realistically this was probably not possible. The ten weapons were test fired into a water tank and the bullets recovered. Copper bullets and lead bullets were both used because the quality of markings left on fired bullets is dependent on ammunition type. A pair of each ammunition type was selected from the test fires to be the experimental sample. The samples were examined by a firearms expert prior to being acquired by each IBIS system.

The bullets were acquired by the same operator who was experienced and had been trained by the manufacturer of the technology. This is a crucial decision by Brinck because the quality of the acquisition of a bullet to each IBIS system can be affected by the operator. The operator has to make decisions about the markings on bullets and the best settings such as focus and lighting that will result in a good quality representation being acquired. One copper bullet and one lead bullet were acquired as reference samples. The second copper bullets and lead bullets were then acquired as known match samples so that each IBIS system could attempt to make the link between the reference samples and the known match pairs.

The background database in this study was provided by the manufacturers of the technology and consisted of 475 bullets of the same calibre as the test sample. The bullets were acquired on IBIS Heritage and then the same bullets were acquired on BulletTRAX 3D. Brinck (2008) does not state whether the same operator acquired the background samples. To maintain absolute consistency, it would have been ideal if the same examiner had at least uploaded the background samples on both IBIS systems. It is probable that these samples were uploaded by an employee of the manufacturer. It is unfortunate that the quality or circumstances of the acquisition of the background sample is not known.

The correlation procedure was performed until the known match sample was found. IBIS (Heritage and BulletTRAX 3D) produces a list of the most probable matches in the database. Brinck (2008) considered any known match falling outside the top twenty to be an unsuccessful correlation reflecting the practise carried out in some ballistics laboratories when using the IBIS systems for casework. Previous research conducted by Nennsteil and Rahm (2006a) and Silverwater and Koffman (2000) suggested that the correlation list should only contain ten objects and five objects respectively meaning that the chance of finding a match in Brinck (2008) was higher simply because the correlation list was longer.

The same operator that uploaded the samples carried out the examinations of possible matches maintaining consistency. The examiner looked at these correlation lists to ascertain the position of the known match. IBIS Heritage and BulletTRAX 3D produce different correlation scores that reflect similarities on different areas of the bullet. Brinck (2008) only considered the max phase score (IBIS Heritage and BulletTRAX) and the peak 3D score (BulletTRAX 3D). Brinck (2008: 678) defined these two variables as, “max phase is the highest score of the bullet-to bullet correlation, where the phase refers to the alignment of the land engraved areas (LEAs) between two bullets.” Peak 3D was defined as “the highest 3D LEA-to-LEA score between the two bullets” (Brinck, 2008: 678). Brinck (2008) stated that these two scores are generally regarded as the most important scores because max phase is the only score that takes the entire bullet into account and Peak 3D is the only 3D score. The choice of Peak 3D is interesting because the IBIS Heritage system is not a 3D system.

For copper bullets, IBIS Heritage correlated 100% of the reference samples to the known match within the top ten matches. Ninety percent of these matches were in the number one position. BulletTRAX 3D correlated 100% of the reference samples to their known match in the top ten and all in the number one position. The results for lead bullets showed that IBIS Heritage correlated 30% of the reference samples to their known match in the top twenty. This essentially meant that 70% of correlations were unsuccessful as they appeared outside the top twenty. BulletTRAX 3D was more successful. One hundred percent of reference samples were correlated to the known match within the top positions. 70% were in the top position with the remaining 30% either in second or third place. In all but one of the instances where the lead bullet was in second or third place, the copper bullet from the same weapon was above it.

Results were also considered when attempting to match lead bullets to the known match sample copper bullet. Using the Max Phase score on IBIS Heritage matching copper bullets to lead bullets, only 20% of the reference samples were correlated to the known match within the top twenty. Correlations performed the other way around (lead bullets correlated with copper bullets) resulted in better performance. Sixty per cent of reference samples correlated to the known match within the top twenty. On all occasions a bullet fired from a different weapon was located higher in the correlation list. BulletTRAX 3D performed better than IBIS Heritage. For copper to lead comparisons, 100% of reference samples were correlated within the top twenty positions. For lead to copper comparisons 90% of reference samples were correlated against their known match within the top ten. The main result that Brinck (2008) describes is that BulletTrax 3D was more successful at identifying bullets fired from consecutively manufactured barrels than IBIS Heritage.

A study carried out by Roberge and Beauchamp (2006) also examined the capabilities of BulletTRAX 3D to identify bullets fired through consecutively manufactured barrels. This study involved consecutively manufactured Hi-Point barrels. Hi-Point barrels have grooves in the barrels that are created by compressing rather than removing the excess material. This results in a shallower barrel groove which in turn means that the barrel is smoother leaving less distinguishable marks. Each shot that is fired causes some of the metal tailings to break off. This process changes the striation marks on the bullets. Roberge and Beauchamp (2006) used bullets fired from ten consecutively manufactured Hi-Point barrels. Twenty pairs of 9mm Luger bullets were used along with one pair of 9mm Luger bullets. The twenty pairs of bullets all had the same class characteristics and the single pair of 9mm Luger bullets had different class characteristics than the set of twenty. The first ten pairs of bullets were numbered 1 to 10 and each was connected to ten known, different barrels. The remaining eleven pairs of bullets were labelled A to K. The purpose of the test was to match each numbered pair to a unique lettered pair. Forensic Technology Inc, the manufacturer of BulletTrax 3D undertook this experiment. The results of this experiment are difficult to verify since the authors' state: "The actual results cannot be revealed here to ensure confidentiality of the original key." (Roberge and Beauchamp, 2006:172). However, they also state that "the accuracy of the re-lettered key has been confirmed with a perfect score of 10/10 by Evan Thompson in a private communication" (Roberge and Beauchamp, 2006:172).

The fact that this study was carried out by the manufacturer of the technology means that the credibility of the findings is somewhat undermined. There is a potential conflict of interest because any negative results would affect the reputation of the technology. For this reason, the findings should be treated with caution. Table 2-5 summarises the success rate percentages from previous research conducted with bullets.

Table 2-5: Bullet Success Rate Percentages from Previous Research

Author	Ammunition	Success Rate (Top 10)
Brinck (2008) IBIS Heritage	Copper jacketed bullets	100%
Brinck (2008) IBIS BulletTRAX 3D	Copper jacketed bullets	100%
Brinck (2008) IBIS Heritage	Lead jacketed bullets	30%
Brinck (2008) IBIS BulletTRAX 3D	Lead jacketed bullets	100%
Nennsteil and Rahm (2006b)	Not specified	50-75%

Experiences using ballistics analysis systems have been reported by firearms examiners working in the field. Giverts (2004) described the problem posed by polygonally rifled barrels. Glock, Heckler & Koch and Israeli Military Industries (IMI) are three examples of manufacturers that produce weapons with polygonally rifled barrels. Polygonal rifled barrels produce markings on bullets that are difficult to examine. This is because the land and groove impressions have a rounded appearance instead of a rectangular profile that is found with traditional rifling (Heard, 2008). Giverts (2004) described how during the bullet acquisition process the operator has to define the top and bottom of a land engraved area and the angle of the striations. The system then performs correlations based on these areas. The top and bottom of the land engraved areas are very difficult to define on bullets that have been fired by polygonally rifled barrels. Giverts (2004) suggested that slight modifications can be made to improve the acquisition of bullets fired from polygonally rifled barrels when using IBIS Heritage. The experiences reported by Giverts (2004) highlight the importance of assessing the functionality of systems in varied conditions and disseminating the results to other practitioners.

The National Academy of Sciences report (Cork et al, 2008) reviewed previous conducted research (Tulleners, 2001; De Kinder, 2002b; De Kinder, Tulleners and Thiebaut, 2004; George, 2004a; George, 2004b). The conclusion reached was that in relation to implementing a reference ballistics imaging database, the IBIS Heritage technology was unsuitable for three reasons. The first related to the fact that IBIS Heritage is based on two dimensional images and as such was not accurate enough to successfully generate matches given the fact that the database size would be considerably large.

Secondly, Cork et al (2008) concluded that there was "un-derived measure of similarity between and within gun types" (Cork et al, 2008: 4) meaning that the number of suggested matches would be too great to be useful because of this inherent similarity. Thirdly, Cork et al (2008) identified the fact that variables such as ammunition type can cause errors in identifications and this would cause problems in practice. They described how the reference ballistics imaging database could be controlled and only contain one type of ammunition but there is no way to control the ammunition used in crimes. Cork et al (2008) also made a number of suggestions as to how technology in this field could be improved including hinting at interoperable systems. They state that "removing strict dependence on a sole-source provider and ensuring government ownership of and access to result data – should be applied to all work related to the improvement in ballistics evidence analysis" (Cork et al, 2008: 7-8). It is also suggested that three-dimensional techniques are applied to ballistics analysis.

Despite the problems with current technology described by Cork et al (2008), ballistics analysis systems can have a high impact on ballistics examinations when installed. Braga and Pierce (2004) assessed the impact that IBIS Heritage technology had on the Boston ballistics department which previously had no ballistics analysis system installed. Braga and Pierce (2004) analysed the number of matches identified between ballistics exhibits for a thirteen year period between 1990 and 2002. IBIS Heritage was introduced in June 1995 and the authors assessed the impact of the technology taking into account other variables such as the number of firearms examiners. They found that IBIS Heritage technology increased the productivity of the police department and that six times more matches were being found after installation. The research carried out by Braga and Pierce (2004) showed that ballistics analysis systems can be an effective tool in investigating gun crimes. This is especially true in situations where there has been no previous technology installation and the comparison is between human examiners and ballistics analysis systems.

Table 2-6 Presents a summary of research conducted into ballistics analysis systems and shows the system that has been studied.

Table 2-6: Summary of Research Conducted into Ballistics Analysis Systems (Chronological Order)

Authors and Year	CC or Bullets	Title	System
Chan (2000)	CC	The relationship between acquisition positions of cartridge cases and discrepancy in correlation scores on IBIS	IBIS Heritage
Silverwater and Koffman (2000)	CC	IBIS correlation results – improvements	IBIS Heritage
Argaman, Shoshani and Hocherman (2001)	CC	Utilisation of the IBIS in Israel	IBIS Heritage
Koffman and Silverwater (2001)	CC	IBIS correlation results – analysing methodology and reliability factor	IBIS Heritage
Tulleners (2001)	CC	Technical evaluation: Feasibility of a ballistics imaging database for all new handgun sales	IBIS Heritage
De Kinder (2002a)	CC	Ballistics fingerprinting databases	
De Kinder (2002b)	CC	Review AB1717 report. Technical evaluation: Feasibility of a ballistics imaging database for all new handgun sales. Independent review for California Department of Justice.	IBIS Heritage
De Kinder Tulleners and Thiebaut (2004)	CC	Referencing ballistic imaging database performance	IBIS Heritage
Braga and Pierce (2004)		Linking crime guns: The impact of ballistics analysis technology on the productivity of the Boston Police department's ballistics unit	IBIS Heritage
George (2004a)	CC	A validation of the Brasscatcher portion of the NIBIM/IBIS system.	IBIS Heritage
George (2004b)	CC	The validation of the Brasscatcher portion of the NIBIN/IBIS system part two: "Fingerprinting firearms" reality or fantasy.	IBIS Heritage
Giverts (2004)	Bullets	Using the IBIS for the examination of bullets fired from polygonally barrelled guns such as the Glock pistol.	IBIS Heritage
Nennsteil and Rahm (2006a)	Both	A parameter study regarding the IBIS correlator	IBIS Heritage
Nennsteil and Rahm (2006b)	Both	An experience report regarding the performance of the IBIS correlator	IBIS Heritage
Roberge and Beauchamp (2006)	Bullets	The use of BulletTRAX-3D in a study of consecutively manufactured barrels	IBIS BulletTRAX 3D
Brinck (2008)	Bullets	Comparing the performance of IBIS and BulletTRAX -3D technology using bullets fired through 10 consecutively rifled barrels	IBIS Heritage and IBIS BulletTRAX 3D
Cork et al (2008)	Both	Ballistics imaging: Committee to assess the feasibility, accuracy and technical capability of a national ballistics database.	IBIS Heritage

2.5.6 Ballistics Analysis Systems Present – Manufacturers other than Forensic Technology

Research to date has focussed on ballistics analysis systems provided by a single manufacturer (Tulleners, 2001; De Kinder, Tulleners and Thiebaut, 2004; George, 2004a; George 2004b; Brinck, 2008; Nennsteil and Rahm, 2006a; Nennstiel and Rahm 2006b; Braga and Pierce, 2004). This research relates to the Integrated Ballistics Identification System (IBIS) suite of products manufactured by Forensic Technology Inc based in Montreal, Canada. This technology has the largest market share of any company. There are other technologies that are available and are now starting to gain prominence in the market. These systems are the Evofinder system produced by Scannbi Technology based in St Petersburg, Russia (Evofinder, 2011), the Arsenal system manufactured by Papillon Systems also based in Russia (Papillon Systems, 2011), the ALIAS system by Pyramidal Technologies based in Barbados (Barrett, Tajbakhsh and Warren, 2011) the Balscan system by Laboratory Imaging in the Czech Republic (Laboratory Imagery s.r.o, 2011) and the Poisk system manufactured by SBC Company in Russia (SBC Company, 2011). In all likelihood other systems will emerge in future. When research commenced in October 2008 there were no published studies that examined technologies that were available other than IBIS products. The report on ballistics imaging produced by Cork et al (2008) for the National Academy of Sciences stated the following, "through IBIS, FTI is essentially the only provider of ballistics imaging technology" (Cork et al, 2008:93). The report proceeds to examine IBIS Heritage in detail but importantly FTI is not the only provider of technology and was not the only provider in 2008. Papillon Systems have had operational systems in Kazakhstan since 1998, in Russia since 2000 and Poland since 2001 (Papillon Systems, 2008). Evofinder in its present form has also been in existence since 2006 although the development of this system can be traced back to 1994 (Evofinder, 2011).

2.5.7 Ballistics Analysis in the Future – New Technology and Alternative Techniques

Current technology is primarily based on digital imaging with the notable exception of IBIS BulletTRAX 3D which is based on confocal microscopy. The main flaw with digital imaging is that three dimensional objects can only be captured in two dimensions meaning that there will always be an inevitable loss of data (Stout and Blunt, 2000). Other technologies and techniques have been suggested or developed and applied to forensic ballistics such as Xie et al, (2009), Chu et al, (2010), Banno, (2004), Geradts, (1994), Field, Kelley and McCabe, (1996) and Nor Azura, Choong-Yeun and Abdul Aziz, (2010).

Xie et al (2009) described how bullets are intentionally made to be larger than the gun barrels that they are fired through. The spiral grooves that are cut into the barrel leave an impression on the bullet, make it spin and ensure that the flight of the bullet stays consistent. These striations are what ballistics analysis systems rely on to correlate different exhibits and produce potential matches. All systems based on imaging rely on and are subject to issues that photography has traditionally faced. These include processing techniques, noise and the general lack of quality of the acquired images. Problems with orientation of the object, lighting and magnification can also affect correlations and make matches difficult. A new system proposed by Xie et al (2009) aims to make the process more deterministic by measuring the markings on an object and comparing these measurements directly without the need to rely on digital imagery. The system proposed by Xie et al (2009) is based on measuring the surface topography of an object and allows objects to be accurately positioned so that setting up the object to be scanned is easy for the user and comparisons with other objects are accurate and reliable. The scanning process starts 1mm from the bottom of the bullet, scans 100 circles aligning the bullet axis with the sample spacing 0.05mm. Each circumference scan consists of 9000 points. The bullet surface topography includes 100 x 9000 points – 900,000 in total (Xie et al, 2009). The advantages of this approach are that the entire surface can be scanned allowing for one hundred percent of information about a bullet to be collected. Systems that rely on images will never be able to achieve this simply because these measurements are in the nano–scale and no existing ballistics imaging technology can capture this degree of intricacy. This means that correlations and comparisons undertaken based upon this data will be highly accurate and reliable and will be highly suited to declaring matches in an automated system.

Another advantage to this approach is that it allows a detailed examination of ballistics components that have never before been able to be measured. Possibly the best example of this is the ability to measure the inside of a gun barrel. Imaging technologies cannot do this because the apparatus they use is too big to go inside a gun barrel. This will allow marks on a bullet to be compared to the gun barrel from which is was fired providing a higher level of accuracy than when comparing a test fired bullet with a recovered bullet.

When a bullet is measured using the surface topography technique described by Xie et al (2009), all characteristics are measured resulting in a digital signature which is made up of class characteristics and individual characteristics. This signal cannot be used directly for comparison therefore the characteristics must firstly be separated. Individual features can be extracted in three steps. The first step is surface abstraction. This refers to the individual characteristics left on the bullet by the barrel of a gun. The twist angle is also imprinted on the bullet and averaging this data can “enhance useful information and suppress disturbances” (Xie et al, 2009: 520). This projection results in a one dimensional signal which represents a faithful reconstruction of the surface of the bullet which improves the efficiency of the comparison. The key calculation that must be correct is the twist angle.

The second stage is wavelet filtering. The one dimensional bullet surface representation described above is made up of class characteristics and individual characteristics. To match two exhibits, these characteristics need to be separated accurately. Wavelet filtering is a form of multi-scale analysis that allows for a high precision level in the time and frequency domain. A high-pass filter is applied to the digital signal and as a result, a profile is obtained that consists of the bullets individual characteristics only. The final step is comparing two objects, achieved by comparing two digital signals. Because the two digital signals represent complete sets of data, correlations and matches are highly accurate.

Xie et al (2009) still suggested that a firearms examiner needs to confirm a match. However, future iterations of this technology may render this step unnecessary. Until this point is reached, Xie et al (2009) proposed a three dimensional visualisation tool that will help an examiner declare a match. The tool will allow an examiner to compare the microscopic marks side by side. There may also be an application for this tool in the courtroom to present evidence to the jury. Such a tool may avoid a situation similar to the case in America in 2003 where the ballistics expert was questioned. In this particular case, the defence lawyer asked the ballistics expert to explain how she had come to declare a match between two cartridge cases. The first cartridge case had been recovered from a gun that the defendant had admitted to firing, the second had been recovered from a murder. In this case, the gun was not recovered so could not be test fired. The ballistics examiner Karen Lipski explained that her conclusion was based on "a lot of experience and knowing what you're looking at." She was repeatedly asked to explain the correlation procedure but could not and suggested that the defence stop focussing on "the number thing." The defendant was acquitted (US News, 2003). A three dimensional visualisation tool would allow a jury clearly see the characteristics that have indicated a match. They should be clear given the accuracy of the measurement and the wavelet filtering technique that separates class characteristics and individual characteristics. Importantly, the accuracy of the surface topography technique removes uncertainty from ballistics examination and presents the facts as they are. Xie et al (2009: 522) claimed that the technique allows acquisition of “complete and accurate” data from an object. This will lead to improved accuracy and will allow significant steps to be taken towards the complete automation of bullet matching as opposed to correlations. It is also possible that this technology could be applied to weapon registration schemes such as the one assessed by De Kinder (2002b). The technology has already been successfully applied to other areas of tool mark analysis (Thomas et al, 2011).

This section has focussed on the forensic processes involved in the generation of evidence and intelligence gathered from ballistics exhibits. A review of techniques, processes and technologies has been presented alongside a discussion of strengths and weaknesses of these techniques, processes and technologies. New technologies have also been discussed along with the impact and improvement these technologies could have on the forensic ballistics process. The next section focuses on potential obstacles new technology might face before adoption and use on a widespread scale. Lessons learnt from other technologies such as Closed Circuit Television (CCTV) and Automatic Number Plate Recognition (ANPR) are discussed and applied to potential new technology in the ballistics field.

2.6 - Potential Barriers to Innovation

The previous section highlighted research discussing the effectiveness of current ballistics analysis technology and also presented new technology that has been applied in this area (Xie et al, 2009; Chu et al, 2010; Banno, 2004; Geradts, 1994; Field, Kelley and McCabe, 1996; Nor Azura, Choong-Yeun and Abdul Aziz; 2010). Innovation and research such as this leads to new technologies, systems and policy ideas that once developed have to be integrated into businesses and organisations such as police forces, law enforcement agencies and laboratories. Often, scientific developments, innovative products and new policies are in danger of failing because of resistance from end-users and implementers. This is a problem that improvements to current technology and any future ballistics technologies will have to overcome. This section examines ways in which similar technology implementations have overcome challenges relating to adoption and in particular looks at experiences with other technologies adopted for crime prevention purposes such as Closed Circuit Television (CCTV) and Automatic Number Plate Recognition (ANPR).

2.6.1 Technology Adoption

Moore (1999) described the idea of a chasm that exists between getting new projects from an ideas stage through to a successful implementation. Moore (1999) outlined the Technology Adoption Life Cycle and the chasm directly linked to this. The technology adoption life cycle consists of five groups into which users are placed. The first group consists of “Innovators” and these people are likely to appreciate technology and be the first to adopt new technology into their lifestyles. The second group consists of “Early Adopters”, best defined as people who find technology useful and appreciate the benefits. The third group is the “Early Majority”. Moore (1999) described this group as having a “strong sense of practicality”. They will adopt a wait and see approach to new technology. There are a lot of people in this group, Moore (1999) estimated that about one third of people in the adoption life cycle fall into this category. It is probable that this is where the vast majority of police forces will fall. The fourth group is the “Late Majority” and these people will wait until a technology is established before buying into it. In the current economic climate, there is the very real risk that police forces will wait for a technology to be established rather than spend money on what might be perceived by others, the media in particular, as a financial risk. Finally, the fifth group consists of the “Laggards”. This group are generally not interested in technology and will not adopt it for a variety of reasons.

The model described by Moore (1999) applies to commercial products and the general population. However, many of the principles apply to police forces which have to procure equipment. They have many of the same motivations relating to cost, value and ease of use that the general population have. The implication of the model developed by Moore (1999) is that successful strategies can be developed to overcome some of the problems relating to technology adoption. It is interesting to consider how ANPR technology progressed from innovative new technology to being used on a wide scale. The process that was used to adopt ANPR on a wide scale in the UK effectively meant that the problems associated with the last three groups described by Moore (1999) (early majority, late majority and laggards) were overcome and the police forces in the UK became early adopters of ANPR technology.

2.6.2 Lessons from the Successful Adoption of ANPR Technology

Henderson et al (2004) explained how ANPR technology allows a vehicle registration number to be read automatically. When used with other data such as location or tax status of a vehicle it is powerful at detecting and preventing crime. Henderson et al (2004) explained how the potential of ANPR was recognised and a phased but targeted implementation approach was used. In 2002 the Home Office equipped each police force with the necessary tools to use ANPR. However, the technology was used at first with dedicated intercept teams. The Home Office commissioned a six month pilot study with nine forces called Laser 1. Henderson et al (2004) detailed the number of cars stopped and the result of these stops. 39,188 vehicles were stopped, over 3,000 people arrested and 45,000 further actions were taken. An independent evaluation concluded that ANPR was effective at disrupting criminal activity. Henderson et al (2004) explained how despite the initial positive results, the widespread installation and use of ANPR technology was delayed due to cost.

A further feasibility study called Laser 2 was commissioned with the specific aim of assessing the cost relative to the income generated by fixed penalty notices. An assessment of the Laser 2 feasibility study indicated that ANPR was an effective policing tool. In the United Kingdom, ANPR technology was phased into everyday policing in a way that enabled some of the obstacles of technology adoption to be overcome. Moore (1999) described five groups of people and the ways in which they adopt technology and suggested that personal and economic reasons are the main factors behind the Technology Adoption model. While this model is perhaps more suited to commercial products, there will be police forces that fit into these categories and people within police forces that also fit into the categories. Often the economic reasons will dictate which group a police force as an organisation fits into but there will also be individuals within police organisations that have a surprising amount of control over which new technologies are implemented. However the approach taken by the Home Office with ANPR described by Henderson et al (2004) mitigated many of the problems described by Moore (1999). By commissioning feasibility studies, the Home Office removed some of the barriers to adoption. The feasibility of the technology was proven in a real world situation meaning that there was not a long gap between a technology being available and it’s worth being proved. The lesson from ANPR implementation is that any new ballistics technology needs to be introduced and its effectiveness assessed at the same time. This allows a relatively fast assessment of worth and removal of doubts from organisations or individuals less inclined to innovate or adopt new technology.

2.6.3 Lessons from the Successful Adoption of CCTV Technology

Closed Circuit Television (CCTV) is installed in many locations for private as well as for law enforcement purposes. It is estimated that there are 4.2 million CCTV cameras in Britain (Norris and McCahill, 2006). Gill and Spriggs (2005) described a number of theories as to why CCTV works and these theories also explain why CCTV was adopted so quickly and widely. The first theory behind the law enforcement use of CCTV was that it represents a visible deterrent for potential criminals and raises the risk of them getting caught. Secondly, CCTV may make people feel safer so in turn more people use the area and an offender's risk of being caught is again raised. Thirdly, CCTV can help with the deployment of police officers. Fourthly, the presence of CCTV may encourage the public to be more vigilant against crime and finally, interventions by the public might be encouraged by the presence of CCTV.

However, successful adoption of CCTV was dependent on a number of variables and whilst the general perception might be that CCTV is used routinely, successfully and on a wide scale, new CCTV installations still have barriers to overcome to ensure successful adoption of the technology. Gill and Spriggs (2005) described five factors that influenced the effectiveness of CCTV and these factors can be applied to future innovations in the forensic ballistics field. The first factor was that a project has clear objectives and was not installed purely for the sake of having it there. Applied to ballistics, this would mean that any new schemes especially with regards to data sharing would have reasonable expectations attached to them as any new technology with unreasonable expectations will fail. Any new ballistics technologies would also have to be proven to be needed and effective such as was the case with ANPR (Henderson et al, 2004). Research carried out by Morris and Dillon (1996) suggested that meeting the requirements of the end users and having clear objectives was important in project adoption. If the benefits of a new system can be seen before implementation and in their intended context then the new technology will be adopted successfully.

The second factor critical to successful adoption was that the use of CCTV was managed properly in terms of use by end users and also by a suitably qualified project manager. Gill and Spriggs (2005) explained how some CCTV schemes did not engage properly with the police and this resulted in the police being reluctant to use evidence provided by the cameras. The police were also reluctant to share intelligence with the operators meaning that some operators might not understand the relevance of events they were monitoring. A similar problem might be faced by innovations in ballistics as any new system will have to be managed effectively in terms of the data that is inputted and shared. The police will also need to actively engage with new systems and share data to avoid a situation where no information is uploaded to a system.

The third factor that influenced effectiveness was technical details relating to the installations of the cameras. This could be the camera positioning and the area covered and the number of cameras in a particular area. This factor related to understanding the technical capabilities of the technology being installed and ensuring it was used properly to fully maximise the benefits. In ballistics, this could be the correct use of ballistics analysis systems and understanding the best configuration of each system to get the best possible results. Such factors might be the best way to position an object or the best lighting angle. Technology adoption in the law enforcement arena will not be successful if the technology is not used as intended (Bean, 1999). If a technology is not used properly and is producing poor results users will often blame the technology when it is the configuration of the technology that is to blame.

The fourth factor described by Gill and Spriggs (2005) was the technical characteristics of CCTV cameras such as the type of camera and its functionality. These characteristics are directly related to the proper use of the technology. For example, certain functions would be more appropriate for deterring offenders (a large, visible, marked camera) than for providing evidence (good image quality).

Calvin and Goh (2005) examined technology acceptance amongst 430 American police officers using a new laptop based system to access crime databases, write reports and dispatch officers to events. The main finding of this research was that information quality, ease of use; usefulness and the time taken for the technology to respond were the most important features. Calvin and Goh (2004) suggested that the acceptance of new technology can be improved by focusing on these factors and that procurement should focus on systems that are effective in these areas. In ballistics, it is not currently understood how ballistics analysis systems work and how they are different. This means that laboratories cannot choose the most appropriate technology for their circumstances. For example a laboratory with a large caseload may need a system that captures bullets and cartridge cases in the shortest possible time (a principle suggested by Calvin and Goh, 2005) and they may be prepared to pay extra for this. Another laboratory may not have a large caseload and may be content to procure a cheaper system that takes longer to acquire samples. Successful adoption relies upon these facts being known and consequentially informed decisions can be made. In ballistics this is not currently the case.

The fifth factor identified by Gill and Spriggs (2005) was the operation of the control room. Specific factors included the hours of monitoring and the communication between the police and the public that provided useful intelligence. The parallel to new ballistics technologies would be to ensure that the human processes surrounding new technology are taken into account and altered where necessary. Ammenwerth and Mahler (2006) examined IT adoption in a medical setting and showed that there is a clear interaction between individuals, the technology they are being asked to use and the tasks they are expected to perform. They suggested that when a new system is implemented, organisational changes often happen and these should be managed carefully. There is a clear parallel here with the law enforcement community. The physicians blamed the new system for their increased workload when in fact the real issue was the new task they were being asked to complete.

The successful adoption of ANPR was aided by the scientific approach to assessing the feasibility of such a scheme and the effectiveness of the technology. This approach has also been applied to CCTV not only to ensure successful initial adoption but successful continuing utilisation of the technology. Notable research includes Waples and Gill (2006), Welsh and Farrington (2009), Farrington et al (2007) and Waples, Gill and Fisher (2009). These studies have all attempted to scientifically quantify the impact of CCTV on crime in a specific setting and as a result guidelines are issued to police forces to ensure successful implementation (Gill, Rose and Collins, 2005). Successful adoption of new ballistics technologies will also depend on rigorous scientific analysis of the effect of the technology on the prevention and detection of crime.

CCTV has also faced other problems such as those described by Fay (1998). These include accusations that CCTV has been adopted for political reasons rather than for its efficacy. CCTV schemes have also faced angry reactions from people living in targeted communities (Guardian, 2010). Other problems faced by CCTV include the possible invasion of privacy and controlling access to the data and sharing of the data.

Closed Circuit Television (CCTV) and Automatic Number Plate Recognition (ANPR) are now widely used in the UK to prevent and detect crime and to provide intelligence. There has also been the suggestion that the perception of the effectiveness of technology such as CCTV and ANPR has led to a wider drop in overall crime rates (Farrell et al, 2010). However, both technologies had to traverse the path from innovative new technologies to being adopted on a wide scale. There will inevitably be implementation issues that any new technology will have to face and overcome. These issues are not trivial and will require considerable time and effort. There will need to be an understanding of the different processes and existing systems that are involved in investigations that have a ballistics element. The main difference between the above points and ballistics analysis is that new and existing technologies relating to forensic ballistics do not involve the capture, storage or exchange of personal data. This means that the security and data protection issues surrounding CCTV and ANPR data are not always applicable to ballistics. Furthermore, the interpretation of ballistics evidence such as bullets and cartridge cases requires a high level of expertise. The barriers to innovation facing ballistics are likely to concern implementation rather than legal issues relating to privacy, data protection and proportionality.

Chapter 3 – Aims and Objectives

3.1 - Areas for Innovation Identified by the Literature Review

3.1.1 Gaps in Knowledge

The review of the literature has revealed areas where innovative strategies and interventions could be implemented to improve current processes and technology with the aim of reducing crimes involving firearms, improving the forensic ballistic process and increasing the detection rate of these crimes. Statistics that report the extent of crimes involving firearms were presented by Smith et al (2010). However, a major weakness of relying on official statistics to quantify the nature and characteristics of any crime type is the fact that unreported crimes are not included in the analysis. This means that it is virtually impossible to provide a full, accurate assessment of the number of crimes involving firearms that have occurred in the United Kingdom. Consequently it is difficult to perform meaningful, complete analysis of these crimes. Squires (2008) described the intelligence gap created by this problem. Crimes involving firearms that occur but are not reported, results in a situation where witnesses and victims cannot be interviewed, the circumstances of the crime cannot be documented and shared and exhibits cannot be examined to yield forensic evidence and intelligence. Furthermore, other crimes may be linked to the incident, but because of a lack of reporting, the link might not be made. The details of the crime and any evidence or intelligence generated, are also unavailable to be utilised by police officers investigating other potential linked offences.

3.1.2 Unreported Crimes

To address this issue, more innovative strategies are needed to understand the extent of unreported gun crime with a view to understanding the intelligence and evidence that can be gained. Pershad et al (2005) and Crewdson et al (2009) examined medical data relating to gunshot wounds to try and address this problem. It is possible that studies such as this could lead to full implementation of a reporting scheme whereby doctors are obliged to report admissions to hospital as a result of gunshot injuries. This is now the case in the UK (Morris, 2009). Careful management of such schemes by law enforcement agencies would not only enable more data to be collected in terms of the number of incidents occurring but could also encourage victims to officially report the crime of which they have been a victim. Another approach would be to examine the problem pragmatically with a view to obtaining intelligence from the incident even if a crime report is not made. Perhaps a procedure could be developed where a victim can provide intelligence about the crime to the police without making a formal report. Although not ideal, at least some intelligence and potential evidence may be able to be gained from the event rather than none at all.

The gap created by unreported crimes was also addressed by Bennett and Holloway (2004) who interviewed offenders with a view to understanding underlying factors that affect crimes involving firearms. Again, this study provided useful data that could be used to quantify gun crimes. Such an approach could also be used to generate intelligence around the circumstances of such crimes. Although requiring careful management as was the case with the medical data examined by Pershad et al (2005) and Crewdson et al (2009), such an approach could contribute to addressing the intelligence gap created by unreported crimes involving firearms.

3.1.3 Using Data Effectively

It should be pointed out that data generated through alternative methods such as those utilised by Pershad et al (2005), Crewdson et al (2009) and Bennett and Holloway (2004) are best exploited and used to prevent future crimes only if that data are used and shared effectively. Increased data sharing can lead to trends being uncovered and this may allow preventative strategies to be implemented. Effective data sharing in this context means it should be shared confidentially and coherently and with the correct agencies and people. Additionally, it is not just the act of data sharing that can make a difference but the actions that are taken as a result of the data being shared. There are different aspects of this problem that need to be overcome. The first is technical and relates to the interoperability of systems whether they are crime reporting systems or forensic systems. However, the value of technical innovation can be undermined if there are not the appropriate legal frameworks and policies in place for the exchange of data. This causes a cyclical problem as often the feasibility of an approach is required to be demonstrated before the appropriate legal changes can be implemented. However, if such an approach is not possible because of legal issues it is very difficult to demonstrate feasibility. This can be addressed in a variety of ways. To demonstrate the feasibility of sharing crime data, prototype systems can be built using dummy data. If real data are to be used, then strategies can be put in place to manage the prototype development and any generated information or intelligence.

There is a wealth of information that could be utilised from unreported crimes. However, it could also be argued that more innovative strategies are needed to take advantage of all the evidence and intelligence opportunities presented by those crimes that are reported and where forensic evidence is available. This is especially true with regards to potential forensic evidence that can be obtained from bullets, cartridge cases and recovered firearms. Although crimes involving firearms (including air weapons) only accounted for 0.3% of all recorded crime in 2008/09 (Smith el al, 2010), when they do occur they generate strong media coverage and the impact on the victims and community is likely to be high. Enhancing and improving forensic practises and increasing the likelihood of detections could improve public confidence in police investigations of gun crime and perhaps address the reluctance of some witnesses to come forward.

It is important to consider the use of automated ballistics analysis systems to investigate and uncover links with other crimes. These systems do not match objects but instead suggest potential matches to a ballistics expert. Research that considered the success rates of a series of experiments indicated that the success rate of the one of the most widely studied systems is around 75% - 95% for cartridge cases and 50% -75% for bullets (Nennstiel and Rahm, 2006b) depending on the circumstances of use. This immediately raises the possibility that there is evidence and intelligence concerning linked events present in the databases of law enforcement agencies that has not been discovered. One of the implications of the work conducted by Nennsteil and Rahm (2006b) is that there is definite room for improvement in the abilities of ballistics analysis technologies to discover previously unknown links to other crimes.

3.1.4 Ballistics Analysis Systems

As previously discussed, there is an intelligence gap created by crimes involving firearms that are not reported to the police. It is therefore vital that evidence and intelligence generated by those crimes that are reported, once discovered and analysed, is used effectively. This includes forensic ballistics data generated by automated systems. Also, as previously stated, data sharing is one tactic that can be employed to address this problem but that the lack of interoperability between systems produces a barrier to effective data sharing. There is currently no interoperability between different ballistics analysis systems. For example, Germany, Switzerland and Belgium all use the Evofinder system produced by ScannBi Technology while the United Kingdom uses the IBIS Trax 3D system produced by Forensic Technology Inc. This produces a very practical difficultly of the United Kingdom not being able to share data generated by the IBIS Trax 3D system with other countries not using IBIS despite the fact that there are documented examples of firearms being trafficked to the UK from continental Europe (BBC, 2003, Guardian, 2007). It stands to reason that firearms that have originated outside the UK may have been used prior to their arrival in the UK and that evidence linking these crimes may be available in databases which cannot be queried in an automated, routine manner. The lack of interoperability between systems is the main factor that contributes to this problem.

This Thesis is primarily concerned with the forensic evidence that can be gained from bullets and cartridge cases through the use of an automated ballistics analysis system. Bullets and cartridge cases can yield intelligence and evidence relating to the weapon that fired them through the distinguishing marks that are imprinted on them as the weapon is fired. Ballistics evidence however, is different to other disciplines of forensic science such as DNA and fingerprint identification. This is because whilst fingerprints and DNA remain constant throughout a person's life, the identifying marks of a gun imprinted onto a bullet or cartridge case change every time the weapon is fired because of the physical contact between components of the weapon and the ammunition and consequential wear of the contacting elements within the firearm. This can result in a situation where two bullets fired from the same weapon will bear marks that match but also potentially marks that do not. This has resulted in there being an element of subjectivity inherent to the discipline of firearms identification. Whilst not necessarily a negative aspect or a disadvantage of firearms identification, this subjectivity does need to be managed carefully, in terms of the way such evidence is presented in court and explained to the public and the ways in which examinations are conducted and conclusions drawn. While DNA and fingerprints evidence have been challenged, robustly defended and tested to the point of widespread acceptance, it can be argued that the same has not happened in the field of forensic ballistics. DNA match probabilities have been clearly defined, discussed and published (Foreman and Evett, 2001; Gill, 2002) - there is no statistical equivalent for match probabilities or error rates in firearms identification (Chumbley et al, 2010).

Successful examination of ballistics items and reliable generation of evidence undoubtedly relies on the skills and experience of human examiners. Whilst attempts have been made to automate the process using computer technology, because of the element of subjectivity and the lack of standards in place for identification, there are no underlying principles which automated systems can or have been built upon. Neither are there identifying processes employed to reliably identify objects to a high or even a known degree of certainty. This has resulted in the manufacturers of such technology using their own techniques, algorithms, correlation procedures and match probabilities to produce these systems resulting in a situation where there is no interoperability between systems produced by different manufacturers. It may be the case that as a result of the lack of standards and lack of rigorous identification criteria, the development of technology in this field has been focussed on providing lists of potential matching candidates rather than actual matches. Ballistics analysis systems do not generate matches. Instead the ranked lists of objects that are similar to the object in question are examined by a ballistics expert to generate evidential matches. However, within each system, data capture techniques and comparison algorithms are utilised and repeated in a consistent manner. It is fair to suggest that careful examination of this technology and the results they yield could potentially contribute to the debate on matching standards and certainly to the debate on interoperability between systems. To date there is a lack of empirical evidence that addresses the feasibility of interoperable systems. As the systems that are currently available are assumed to work differently and produce different results, work needs to be undertaken to document these differences and the variance in the results produced.

This Thesis aims to plug this gap in our knowledge and capabilities by developing a methodology to enable this to happen. The key to enabling these differences to be mapped is a controlled experiment using the same data set for each technology. Each system should be employed to capture and correlate the same identical sample of bullets and cartridge cases. This ensures that any variance in the results is produced by variances in the functionality and capabilities of the systems rather than the sample of ammunition. Documenting these differences is the first step to being able to design solutions to overcome them and achieve interoperability.

3.1.5 Gaps in Research Concerning Ballistics Analysis Systems

There has never been a comparative analysis published of the different ballistics analysis technologies that are available using a standardised data set. This prevents laboratories from being able to make fully informed decisions as to which technology they procure. Previous research has concluded that it is difficult to compare the results of research even when the same system has been examined. Nennstiel and Rahm (2006a:18) state,

> *"Extensive IBIS instrument tests have been conducted in the past with different goals in connection with these and other studies. Their results, standing alone, however, are difficult to compare with each other. A systematic summary is lacking to determine which parameters have an influence on the success or error rate, respectively, during the operation of the IBIS system."*

Due to the lack of academic, published research examining other systems, it is logical to suggest that the above statement can be applied to other technologies. It is also logical to suggest that the only way of enabling a comparison of results generated by different systems is to design a methodology with this purpose in mind and to use the same dataset for every system that is to be examined now or in future. All studies published to date have examined each system in isolation with the exception of Brinck (2008) who examined IBIS Heritage and the newer IBIS BulletTRAX 3D system. There has been no published research on the potential for interoperability between different systems currently in operation and the impact this could have on the investigation of gun crime. An essential prerequisite to any work on interoperability between systems is a thorough understanding of the ways in which the systems work including data acquisition and correlation procedures. A complete understanding can only be gained with the full cooperation of the manufacturers of these systems. However, careful examination of the results produced by each system will provide information on the inherent variance between the systems and will provoke a debate as to whether or not interoperability is possible. There are no data available currently that would allow the variance between systems to be recorded and analysed and, as such, there is a lack of evidence contributing to the debate on interoperable systems. The focus of this Thesis is the ballistics analysis systems, the data they produce and innovations that could contribute to the police investigation of gun crime. Previous research in this field has been important in the design of the methodology and the targeting of the research aims. The methodology that will be outlined in Chapter four builds upon and extends prior research in this field and has also attempted to address some of the methodological issues present in prior research.

As previously discussed, earlier research has focussed on technology from a single provider, namely Forensic Technology Inc. An example is the study conducted by Nennsteil and Rahm (2006a) and published in the Journal of Forensic Sciences. In this research, the authors defined many of the variables that contribute to the success rate of the system. This study and others (Tulleners, 2001; De Kinder, Tulleners and Thiebaut, 2004) subsequently contributed to the debate as to whether or not a system such as IBIS Heritage could be used to collect the markings from legally held weapons (Cork et al, 2008) in a reference ballistics imaging database[10]. Despite the fact that the authors have attempted to describe multiple variables that affect the outcome, the study only examines the IBIS Heritage system.

The research conducted by Argaman, Shoshani and Hocherman (2001) provided a good example of how the IBIS Heritage system was used in the field in real case work and contained useful information on procedures that proved particularly effective for the police in Israel. Whilst this research did provide useful information there are two main issues with the research. Firstly, the study only considered the IBIS Heritage system, not surprising given the fact that the only system installed in Israel was IBIS Heritage. The second issue is that there were no specific metrics provided with the findings about the size of the database examined, or the samples upon which conclusions were drawn.

The research conducted by Brinck (2008) only examined IBIS. Although it should be noted that unlike other studies considered, Brinck (2008) did compare two technologies – the IBIS Heritage system and the BulletTRAX 3D system. There are therefore points relevant to the comparison of the systems that can be taken forward. An additional element of complexity is inherent in the research conducted by Brinck (2008). Specifically the fact that the comparisons between the systems were conducted on the basis of bullets fired from consecutively manufactured barrels. Bullets test fired and recovered using consecutively rifled barrels should be more difficult to distinguish between. This is because the

[10] A Reference Ballistics Imaging Database (RBID) refers to a database of cartridge case and / or bullet images acquired by an automated system. The purpose of a RBID is to acquire cartridge cases and bullets from legally held weapons so that bullets and cartridge cases recovered from crime scenes can be compared against bullets and cartridge cases from legally held weapons.

minute imperfections caused by the manufacturing process should be less obvious because the barrels have been produced consecutively. This should result in there being less chance that the manufacturing components have had chance to wear out so the differences between each barrel should be very small.

A potential weakness of the research conducted by Brinck (2008) concerns the background sample of 475 bullets that was provided by the manufacturer of the technology. It is therefore difficult to verify the background sample in terms of tracing the source weapons and ensuring the production of the test fires under controlled conditions. It is also highly unlikely that the manufacturers would allow the background sample to be used in further research with another technology provider. The research conducted by Brinck (2008) also only concerned bullet analysis.

The research conducted by Roberge and Beauchamp (2006) also concerned the ability of BulletTRAX 3D to identify bullets fired from consecutively manufactured barrels. One of the issues is the fact that the authors are employees of the manufacturers of the technology. There is the potential for commercial interest in a favourable result. As was the case with Brinck (2008) because of the involvement of the technology manufacturer it is unlikely that the research could be replicated with another technology provider.

De Kinder, Tulleners and Thiebaut (2004) assessed the feasibility of a reference ballistics imaging database (RBID). They concluded that such a database would be unsuitable for law enforcement use. However, the design and the explanation of the experiment conducted are thorough, meaning that a full assessment of the variables can be conducted and the results considered in the context of other research. The two main issues with the research conducted by De Kinder, Tulleners and Thiebaut (2004) are firstly that only cartridge cases are considered and secondly, only one system was assessed and this was the IBIS Heritage system. The ammunition used for this experiment was generated from the weapons held by police officers and it is not known if this ammunition could be used with other systems. This research provides a model for further work examining automated systems but also highlights the need to preserve the test sample of ammunition so that different systems can be examined and the results are made immediately comparable.

3.1.6 Examination of Ballistics Analysis Systems – Key Variables

A discussion of work previously conducted in this field has identified a number of key variables that affect the operation and results produced by ballistics analysis systems. All need to be considered in the design of a controlled experiment. The test sample of cartridge cases or bullets that is used is perhaps one of the most important variables. The test sample of weapons that a researcher is attempting to identify in a database will vary depending on the make and model of firearm as well as the make and type of ammunition. Ammunition fired by some weapons is relatively easy to distinguish between whilst ammunition fired from different weapons, notably Glock handguns, can be difficult to tell apart. Ammunition type will also directly affect results. For example, lead bullets are softer and the markings and striations imprinted on them are of different quality than those imprinted on copper bullets. The effect of ammunition type has been noted by George (2004a and 2004b) and De Kinder, Tulleners and Thiebaut (2004).

The choice between a sample of different weapons or consecutively manufactured barrels is important when researching the capability of systems to acquire and correlate bullets. Another crucial variable is the background database used when attempting to correlate objects. Generally, the performance of each system should be considered relative to the database size. If a system can find the known match in the top ten on 95% of trials, then the interpretation of this result depends on the number of other objects in the database. A system achieving this result with 1000 objects in the database could be considered the better performer than a system achieving this result with 100 objects in the database. This is because there are more variables in the database that the system has to consider and discount. Ballistics analysis systems do not match items directly. Rather they correlate them. Correlation procedures indicate the strength and direction of a relationship between variables rather than producing a definitive positive or negative result. The success and results of correlation algorithms and equations are dependent on the many variables involved. In the context of ballistics analysis systems, correlation does not imply a causal relationship instead implying that two objects are similar to each other. It should also be noted that the correlation scores generated by ballistics analysis systems are not traditional correlation coefficients and have no statistical meaning. Instead they are scores generated by the proprietary algorithms of each system. It has been argued that the term correlation is misleading and the term comparison should instead be used (Cork et al, 2008).

The type of weapon that generates the test sample[11] of cartridge cases and bullets is important because some weapons produce marks that are easy to identify and other weapons produce marks that are extremely difficult to identify. Another important point relating to the type of weapon is availability and access to enough weapons to generate an experimental sample of sufficient size. It is for this reason that previous research has used ammunition in open case files or ammunition provided by the manufacturers of ballistics analysis systems. The disadvantage of using ammunition provided by the manufacturer is that it is unlikely the manufacturer would allow the use with a competing system.

[11] Sample is this context refers to the bullets and cartridge cases that are to be acquired by each system.

Some systems require significant input from the operator and some do not. This interaction may involve entering descriptive data about features of the weapon that fired the ammunition such as make and calibre. It may also include descriptive information about the ammunition and the classmarks on the bullets and cartridge cases. This may be the shape of the firing pin impression on a cartridge case or the number of lands or grooves on a bullet or the manufacturer of a cartridge case. Other types of operator interaction may be marking distinguishing features on the captured images of a bullet or a cartridge case. On a bullet this may be highlighting good quality striations to be used in the comparison process and on a cartridge case this could be marking the edge of the firing pin impression. It is important to note that some systems have different levels of required interaction and this interaction will affect the correlation results. The extent to which this interaction affects the results in not known but must be considered when drawing conclusions on the operation and performance of a system. It is therefore important that the operator of a particular system is considered carefully. Considerations might include the level of experience of the operator and the expertise they have using a particular system. Ideally a highly experienced operator would be selected to input the test ammunition to ensure the highest possible data quality.

Another important variable is the geographical location of the research. It has been identified that a gap in the literature is the absence of standardised experiments that can be repeated as many times as is necessary with different technologies. Directly related to this is the sample that is to be used, where it is stored and the availability of the sample to any interested party that wishes to use it in future. Consequently the location in terms of the country where the research is carried out is an important variable. Generally there are two options: firstly the location is the same for all participants. An example might be a dedicated laboratory at a forensic department of a particular country that all participants have to travel to. A second option is a flexible location. This could involve the research being carried out at the headquarters of each manufacturer involving the repeated transportation of the test sample of ammunition. The benefit of a constant location is a greater element of control over extraneous variables that may arise. It is also less likely that samples will be lost[12]. The disadvantage is gaining consensus as to where the location may be and the added costs that may arise as a consequence. The companies that manufacture this equipment are based in different countries and transportation of the ballistics analysis systems to laboratories in different countries can be expensive. There are also associated travel costs relating to the operators of the systems being at that location for the duration of the research. The main advantage of conducting

[12] Due to the difficulties of generating large samples of ammunition for test purposes including time, expense and safety issues, loss of a test sample of ammunition would be extremely disruptive to any experimental research. It would result in the experiment having to start again as using different samples would mean the results would not be comparable.

research at a manufacturers headquarters is that usually there is a system installed that can be used. The disadvantage is that the test sample of ammunition may be lost or damaged during transportation. Due to the dispersed locations of the manufacturers and the quantity of bullets and cartridge cases, the test sample would have to be checked into an aeroplane hold where there is potential for loss or damage.

3.1.7 Gaps in the Literature – Multidisciplinary Research

The literature review has demonstrated that there is a clear distinction between research conducted in the criminology field and the forensic ballistics field. Research conducted in the discipline of criminology has focussed on gun crime – quantifying the extent, characteristics and individuals that become involved. Research in the forensic ballistics field has tended to focus of technical issues such as matching standards, best practice and the performance of technology that can be used to automate parts of the process. There appears to be an absence of work that discusses the criminological implications of forensic ballistics work relating to gun crime. This Thesis aims to address this by placing the implications of the original research conducted, firmly in the context of wider policing issues specific to gun crime. There are some examples of multidisciplinary research that combine forensic ballistics with other disciplines. The example described below combines psychology principles to discuss some of the issues affecting forensic ballistics analysis.

3.1.8 Multidisciplinary Research – Confirmation Bias

Firearms examiners confidently state that procedures in place such as colleagues checking each other's' work counteract any potential for bias but there is little published research that provides the evidence for this. It is important to distinguish between proficiency testing and experiments that examine bias. Proficiency testing usually involves a small sample of ammunition presented to an examiner consisting of matched pairs. The task of the examiner is to correctly identify the matches in the sample. For the potential for bias to be investigated, some form of ancillary information must be presented to the ballistics examiner and the effect of this information measured. While it may be the case that firearms examiners do counteract issues of bias, good scientific process demands that evidence is in place to support the argument. To date there are no published studies that examine the interaction between ballistics analysis systems and human firearms examiners in terms the potential for these systems to introduce bias into the identification procedure.

Kerstholt et al (2010) examined the extent to which firearms examiners were vulnerable to confirmation bias when identifying matches. In this experiment, firearms examiners were given sets of bullets along with information that might bias them towards a particular conclusion or accompanied by neutral information. Kerstholt et al (2010) concluded that examiners were not affected by confirmation bias. However, there were methodological issues with the research which means the results should be treated with caution. The sample size was small consisting of only six examiners and there was no control condition. A control condition would have involved presenting the bullets with an absence of information to enable the variables (the biasing information and the neutral information) to be compared to a condition where no information was presented. The research was also carried out in the Netherlands so there may have been procedures and policies in place in that particular country that affected the results. However, the approach taken by Kerstholt et al (2010) could be modified to address the issue of automated systems introducing bias into ballistics examinations. Risinger et al (2002) explained that one of the ways confirmation bias can be manifested is if more information than is necessary is provided to the examiner. This could be the case when information about potential matches from an automated system is presented to an examiner for confirmation. An approach to documenting the effect this may have on the conclusions drawn by an examiner could be to give a set of bullets to an examiner with the correlation list produced by an automated system with a variety of conditions. These could be where the matching object is in the top position, where the matching object is not in the top position and where there is no matching object in the provided sample. A control condition would be where a set of objects is provided to an examiner but without any information from an automated system. A further dimension to such research would be a comparison of the bias potential of different systems if the hypothesis that different systems produce different results is proven to be true.

To examine the interaction between firearms examiners and the technology they utilise, arguably there needs to be prior work conducted examining the systems themselves both in terms of the ways in which they work, the ways they are used and the results that they generate. This Thesis attempts to address these points by designing a methodology to assess these questions with two systems that are commercially available. The methodology is also designed in such a way as to enable the research to be developed and extended to other systems in future should more systems become available or more manufacturers wish to undergo the procedure. The dataset and results that were used as part of the original research conducted as part of this Thesis could arguably be used for future research to add to the work by Kerstholt et al (2010) by forming the basis for an experiment examining the potential of ballistics analysis systems to introduce confirmation bias into the identification process.

3.1.9 Opportunity for Innovation

Current ballistics analysis technology is based on digital imaging and confocal microscopy. Research to date has indicated that the technology is not sufficiently advanced to allow implementation of a reference ballistics imaging database (RBID) that would allow all newly manufactured guns to be test fired and these test fires acquired[13] by a system and stored in a database (Cork et al, 2008). In the case of ballistic analysis systems described in this Thesis, the underlying technology is based on digital imaging. There is an opportunity for new innovative technology to fill the gap created by some of the documented shortcomings of technology based on digital imaging (Cork et al, 2008). Technology based on digital imaging and also confocal microscopy means that the signature created within the barrel of a gun is impossible to acquire. Technology such as that described by Xie et al (2009) and Barrett, Tajbakhsh and Warren (2011) could be used to provide new systems that offer greater accuracy.

3.1.10 Summary

The literature review has clearly shown that there is a lack of research that has examined ballistics analysis systems other than the IBIS Heritage system. There is also a weakness is all previous research concerning the samples of ammunition used, in that the availability of the samples for further research is not known. This Thesis will attempt to address these two points by designing a methodology that can be applied to any ballistics analysis system regardless of the underlying technological principles employed. This Thesis will also aim to build a test set of ammunition specifically for the purposes of preservation and replication. This will ensure that the research conducted here can be replicated at any point in the future and that the results will immediately be comparable and relevant to research that has previously been conducted. This would represent an original contribution to knowledge.

The literature review has also demonstrated that there is a lack of multidisciplinary research that examines the direct impact of forensic ballistics analysis on the police investigation of gun crime. This Thesis will firstly explain the ways in which ballistics analysis technology and the analysis of ballistics evidence can directly impact upon police investigations. Secondly, as the literature review has suggested, there are areas of forensic ballistics where innovation is needed and where current technology lags behind that in other areas in forensics. This will be considered, investigated and discussed. Thirdly, the importance of innovation in forensic ballistics and its critical importance in preventing and detecting crimes involving firearms will be discussed through the analysis of the experimental results. The multidisciplinary approach demonstrated in this Thesis also represents an original contribution to knowledge. The aims of the Thesis are presented in the next section of this chapter.

[13] Bullet acquisition or cartridge case acquisition refers to the high resolution images being captured by the system and then stored in database to enable correlations to be carried out.

3.2 – Aims

The overall aim of this Thesis is: ***to conduct multidisciplinary research that examines ballistics analysis technology and the results that they produce in the context of data sharing and interoperability. The impact that these systems have on law enforcement agencies investigating gun crime will also be considered.*** Increasing data sharing and moving towards an evidence based debate on interoperable ballistics analysis systems would represent significant innovation in this field.

In order to contextualise the research and to enable a discussion on the impact of innovation in the forensic ballistics field, this Thesis conducted a literature review to examine the issues that are intertwined with crimes involving firearms. This included the links between guns, gangs and drugs and the problems this can cause for law enforcement. The literature review also provided a review of research already conducted on examining ballistics analysis systems. The issue of confirmation bias amongst forensic practitioners was also discussed in the review together with literature relating to the nature and characteristics of gun crime. This enabled the research to be placed in a broader context. Although the research concerns matters that are directly related to ballistics analysis systems and associated forensic ballistic processes, this Thesis is multidisciplinary in nature as it discusses the implications of the research in a broader policing context.

The review of the literature has revealed that there is a gap in reported literature with regards to an analysis of different ballistic analysis systems with the same set of ammunition. Therefore this Thesis aims to produce a standardised data set of test fired ammunition that can be used to assess ballistics analysis technologies and the resultant data. A methodology will also be developed to enable the assessment of the data produced by ballistics analysis technologies. An experiment will also be carried out using this data set and methodology to enable the results to contribute to the debate on interoperable systems and innovation.

As previously stated, this research is multidisciplinary. The results will be discussed in the context of issues directly relevant to policing. These issues include: the contribution ballistics analysis systems could make to close the gap created by unreported crimes; the additional intelligence the systems could yield; the contribution of the results to inform police procurement decisions; the potential for a weapon registration scheme and the contribution that these systems could make to specialist policing operations in tackling gun crime.

The gaps in the literature are summarised below, followed by the research objectives of the Thesis.

3.2.1 Summary of Gaps in the Literature

The principal research identified through the literature review can be summarised as follows:

- There is a clear problem that is created by the fact that some crimes involving firearms are not reported;
- The evidence obtained from those crimes that are reported should be utilised as effectively as possible;
- Percentage success rates of one particular ballistics analysis technology used to automate parts of the process was quoted at 50% - 95% raising the possibility of links between crimes remaining undiscovered despite the presence of the evidence;
- Recovered evidence can be utilised by sharing the data as widely as possible to improve the possibilities of links to other offences being uncovered;
- There is no interoperability between ballistics analysis systems making data sharing between systems impossible;
- An essential pre-requisite to interoperability is a thorough understanding of the ways in which the different systems work and the data and results they produce;
- Research to date has focussed on a single provider - Forensic Technology Inc;
- There has been no published research examining the performance of other systems available;
- There has been no published research examining multiple systems from different providers with the same set of ammunition.

3.2.2 Research Objectives

The principal research objects for the study are as follows:

- To design a methodology to enable ballistics analysis systems to be compared and assessed;
- To produce a test set of ammunition that can be preserved and used repeatedly as required;
- To conduct an experiment with two of the currently available technologies;
- To place the findings of the research in the broader context of police investigations of gun crime;
- To use the results of the research to discuss the potential for innovation in the field of ballistics analysis systems;
- To discuss the potential impact on the police investigation of gun crime that innovation in this field could have;
- To identify the nature and characteristics of potential future innovation in this field.

The next Chapter explains the Methodology employed to achieve the above research objectives.

Chapter 4 – Methodology

4.1 - Introduction to Methodology and Rationale for the Experimental Work

This Chapter explains the experimental methodology that was used to complete the section of work using ballistics analysis systems and the decisions made during the process of developing the experimental design. This Chapter is divided into three Sections. Section 4.1 introduces the methodology and explains the rationale for the experimental work. This section also explores the reasons why research, such as that described in this Thesis has not been conducted before. Section 4.2 describes the background work that was undertaken before the experiment was designed and started. Finally Section 4.3 describes the experimental design and variables involved in the experiment.

4.1.1 Rationale for the Experiment

The experimental design described in Section 4.3, aimed to draw upon and extend previous research that has been conducted in this field. The literature review demonstrated that previous research in this field has focused on just either one technology (Tulleners 2001; De Kinder, Tulleners and Thiebaut 2004; George 2004a; George 2004b; Nennsteil and Rahm 2006a; Nennsteil and Rahm, 2006b), or on two technologies from the same manufacturer (Brinck, 2008). The clear implication of the literature review is that because there is no reported research comparing different systems from different manufacturers under controlled conditions, there is, therefore, a clear need to address this and to design an appropriate methodology to facilitate proper cross technology comparison. Despite the limitations of previous work, the research described in this Thesis should be viewed as inspired by and extending the research themes and ideas developed by researchers such as Tulleners (2001), De Kinder, Tulleners and Thiebaut (2004), George (2004a and 2004b), Nennsteil and Rahm (2006a and 2006b) and Brinck (2008). In addition to extending previous research, there are two fundamental reasons why research should be conducted to compare ballistics systems from different manufacturers and the data they produce. These are now discussed.

4.1.2 Lack of Interoperability between Different Systems

The first reason for conducting this research is that there is no interoperability between different ballistics analysis systems. The images and text data captured by one system cannot be exchanged or correlated with those emanating from systems manufactured by a different provider. The literature review highlighted areas where innovative strategies could be applied to reduce gun crime. One of these is around increased sharing of forensic ballistics data. However as there is no interoperability between ballistics analysis systems, the data that can be shared is limited by the technology a user happens to have procured. An essential prerequisite to any work on interoperability is the creation of a controlled data set generated using the same sample of objects. This will allow the similarities and differences between the systems to be understood. Attempting to compare the data from different systems using different objects will not allow this variance to be understood. This type of comparison analysis often termed “round robin” testing is common in the surface metrology field and measuring system manufacturers are usually willing to contribute (Blunt, Ohlsson and Rosen, 1994; Gao et al, 2008).

Table 4-1 demonstrates the complex nature of interoperability between different systems when there are more than two systems involved. Different technologies use different measuring principles such as grey scale imaging or full confocal microscopy, and consequently the issue of interoperability is not simple to address. A key prerequisite for interoperability would be a common data format and at present this does not exist. It is known that data produced by a single technology can be shared and correlated with data produced by the same technology but from a different physical machine. However, what has never been established is the extent to which interoperability between different systems is possible. For example it may be the case that data from Technology A can be interoperable with data from Technology B but not with data from Technology C. Table 4-1 shows that interoperability between systems is a multifaceted problem and as such it is unlikely that total interoperability between every single system is possible, especially if differing measuring principles are used. Instead it is likely that interoperability will be possible between some systems but not others. In order to find out the extent to which this is possible a controlled experiment such as the one designed in this Thesis needs to be undertaken to understand the differences and similarities between each system.

Table 4-1: The Multifaceted Nature of Interoperability between Ballistics Analysis Systems

	Technology A	**Technology B**	**Technology C**	**Technology D**	**Technology N**
Technology A	✓	??	??	??	??
Technology B	??	✓	??	??	??
Technology C	??	??	✓	??	??
Technology D	??	??	??	✓	??
Technology N	??	??	??	??	✓

Table 4-1 Key: A tick means that interoperability is possible between the systems in question. Question marks mean that the extent to which interoperability between the systems in question is possible is not known.

4.1.3 Progress Towards Interoperability

In order for progress to be made towards interoperable ballistics analysis systems it is theorised that there are a number of underlying factors that need to be documented and understood. It would be unreasonable to expect systems to be able to be interoperable without a thorough understanding of key features. It is assumed that as each system is produced by different manufacturers, each system will, therefore, work differently and use different measuring principles. It is certainly true that these differences are not well understood and are not documented. If the assumption that the systems work differently is true, then it logically follows that the data produced by each system will also be different and in different formats, but again, the differences are not well understood and are not documented. Ballistics analysis systems do not produce definitive matches, instead producing a correlation list of suggested matches. If each system works differently and consequently produces different data, it is a logical assumption to make, that each system will produce different correlation lists even using the same sample of objects. A pre-requisite to interoperability therefore, is an understanding of the differences in the correlation lists and also an understanding of the correlation algorithms and principles upon which the lists are produced. Another essential pre-requisite to interoperability is a thorough understanding of the differences in the images captured by each technology and the meta-data that is captured by the system and whether it is entered by the user or generated by the system. Only when these key features have been studied and documented can a specification be drafted to enable progress towards interoperability.

4.1.4 The Absence of an Evidence Base on the Performance of Different Systems

The second main reason for designing this experiment and conducting this research was that at the time of writing there was no published peer reviewed research that has compared two systems from different manufacturers using the same controlled samples of bullets and cartridge cases. There is research, such as that conducted by Brinck (2008) that has compared two different systems from the same manufacturer. Whilst providing a valuable insight into the technology examined, the two different systems examined by Brinck (2008) will undoubtedly have common features and algorithms. It is probable that systems from different manufacturers will utilise different hardware, software and algorithms but the extent of these differences is not understood. There are good reasons why different systems have not been compared using the same data set, all of which are valid and these are explained in this Section.

Research in this field is difficult to undertake. Previous research conducted in this field has not only focussed on a single technology or manufacturer but has also been conducted by the manufacturers themselves (Roberge and Beauchamp, 2006). Whilst providing interesting results, these tests have not been independently conducted. The fact that the manufacturer of the technology carried out the study, immediately introduced the possibility of bias into the experiment's design and the results. An independent study would be designed with the specific aim of eliminating bias and controlling the experimental conditions. The methodology presented in this Section 4.3 of this Chapter attempts to rectify this situation through a controlled experimental design that is aimed to facilitate high quality results with any technology produced by any ballistics analysis system manufacturer.

Table 2-7 above provides a summary of research conducted to date in this field and shows the system the research was conducted using and whether it was bullet or cartridge case correlation capability that was examined.

4.1.5 Why have Systems from Different Manufacturers not been compared using the Same Data Set?

As explained above, a major reason for undertaking the research described in this Thesis is that there is no peer reviewed published research examining different systems from different manufacturers using the same data set. There are many reasons why this has not occurred before. Many of these reasons are logistical and are described below.

4.1.6 Generating a Test Set of Ammunition

One of the main reasons is that it is very difficult to generate a test set of ammunition that is large enough to use in such an experiment as the one described in Section 4.3 of this Chapter. The weapons that are used to generate the test fired bullets and cartridge cases also have to be "safe" weapons. They cannot be weapons that are either in service or are part of an on-going criminal case. This prevents any ethical concerns over the repeated use and examination of bullets and cartridge cases fired from these weapons. Laboratories that routinely undertake ballistics analysis have reference collections of firearms that are used for research purposes and it is these weapons that should be used for research of this type. However these reference collections vary in size and content. The time and organisational demands of generating such a test set of ammunition are considerable and the majority of ballistics experts have casework as their priority.

4.1.7 Location of Ballistics Analysis System Manufacturers

The current market situation with regards to ballistics analysis technologies also presents a problem because the companies that manufacture this equipment are located in different countries around the world such as Canada, Russia, Czech Republic, Germany and Barbados. There are inherent difficulties in designing such an experiment because the decision would have to be made as to whether to take the test ammunition to the companies or to bring the companies to the test ammunition. Both approaches have potential problems but also advantages and either approach presents logistical challenges. The market has also been dominated in recent years by a single supplier so it could be argued that there has not been the will on the part of the community to undertake such an experiment. However the expense of ballistics analysis systems combined with public sector spending cuts has resulted in increased will on the part of the ballistics community to examine technology from different providers.

4.1.8 Difficulties using a System Installed in a Working Laboratory

Conducting experiments using ballistics analysis systems also presents a problem for the users of the systems simply because these systems were purchased for the purpose of conducting real life casework. Taking a system and a human operator offline when casework needs to be done presents an ethical dilemma because no matter how interesting or valuable the research objectives, priority is always given to real cases. This situation means that any research using these systems is usually conducted when the users have spare time and resources and consequently takes longer. There are also considerations that have to be taken into account such as ensuring that the test samples for the research are partitioned and separated from the open case file.

4.1.9 Time it takes to acquire a Large Test Set of Ammunition

For the results of an experiment to be valid, a relatively large sample of ammunition needs to be used. This presents a problem because it takes a long time to acquire a sample of ammunition using just one ballistics analysis system. For example, if the average time to acquire a bullet is ten minutes and there are 400 bullets to acquire, this would take almost two full working weeks to complete. Obviously the time needed increases for every additional system that is to be compared. The systems cannot run the experiment in parallel because there is only one test set of ammunition.

4.1.10 Financial Implications of Conducting such an Experiment

An experiment such as the one described in this Thesis costs money. The materials needed such as the test fired weapons cost money and the time of experts also incurs a cost for the organisation that employs them. Furthermore there are costs that the manufacturers would have to incur. These could be time and labour costs for their members of staff involved in the experiment, or costs relating to the logistics of carrying out the experiment and transporting the relevant equipment. It is probable that in the past these costs have proved to be prohibitive to carrying out this kind of research.

4.1.11 Difficulties Experimenting with Systems from Different Manufacturers

Any experiment where there is a perceived element of competition is going to create difficulties regardless of how well intentioned the aims of the research. It is probable that in the past, companies have declined to participate in such research because of commercial sensitivities that would inevitably arise from the eventual results.

The author and collaborators have faced all of the problems described in this Section and a major part of the work for this Thesis and the development of the experimental design was concerned with finding ways to overcome these problems. The ways in which these problems were overcome are explained later in this Chapter in Section 4.3.

4.2 - Background to the Experimental Research

This section describes the background work that was undertaken prior to designing and commencing the experimental research.

4.2.1 Understanding Current Ballistics Technologies that are Available

The first stage of the work was to understand the different technologies that are available. This was achieved through internet based research and a review of the available literature. As a result of this stage of work, it quickly became apparent that a comprehensive review was needed describing the technologies that are currently available in terms of functionality, data produced and the sites where they were installed. However, there was very little information available about the systems beyond the marketing material produced by each company. The systems and manufacturers and the base countries of the manufacturers are listed in Table 4-2. As of September 2011 Table 4-2 lists all known the systems that are available globally.

Table 4-2: Ballistics Analysis System Manufacturers

System Name	Manufacturer and Country where Based
Evofinder	Scannbi Technology (Germany and Russia)
Arsenal	Papillon Systems (Russia)
IBIS Heritage	Forensic Technology Inc (Canada and Republic of Ireland)
IBIS Trax	Forensic Technology Inc (Canada and Republic of Ireland)
Poisk	SBC Company Limited (Russia)
Condor	SBC Company Limited (Russia)
Alias	Pyramidal Technologies Limited (Barbados)
Balscan	Laboratory Imaging (Czech Republic)

As part of the research for this Thesis meetings have been held with each manufacturer either at the head office of each manufacturer or at relevant industry events. These meetings were held between March 2009 and May 2010 and were vitally important to the Thesis because they enabled a greater understanding of each particular technology and they also allowed the author to assess the level of potential co-operation that might eventually be realised. Table 4-3 lists the meetings that have been held.

Table 4-3: List of Meetings Conducted and Manufacturers Visited

System and Manufacturer	Location of Meeting	Dates of Meeting
Evofinder (ScannBi Technology)	Wiesbaden, Germany	1st-3rd April 2009
Balscan (Laboratory Imaging)	Prague, Czech Republic	22nd-24th April 2009
Arsenal (Papillon Systems)	Miass, Russia	3rd-8th May 2009
IBIS Heritage and IBIS Trax (Forensic Technology Inc)	Dublin, Republic of Ireland.	6th-7th October 2009
Alias (Pyramidal Technologies)	Wiesbaden, Germany (at the 2009 ENFSI firearms working group meeting.)	20th-23rd October 2009
Condor and Poisk (SBC Company)	St Petersburg, Russia.	13th-18th May 2010.

As a result of this stage of work encompassing internet based research, the literature review and visits to the manufacturers, there was a clear understanding of the ballistics analysis systems available and the companies that manufacture them. There was not however a thorough understanding of the functionality of the systems and the data produced by them.

4.2.2 Background to and Evolution of the Experimental Design

In May 2009, the author visited one of the technology manufacturers and as a result of this visit a decision was made to pursue the scientific assessment and comparison on technologies in order to explore the opportunities for interoperability. This decision was prompted by the fact that this manufacturer expressed frustration at the lack of published scientific research and suggested that comparisons of different technologies do take place within organisations for procurement purposes but that the results are kept confidential. This company also supported the idea of interoperability between systems and were willing to engage in research to further this aim. They also agreed to provide a ballistics analysis system to the author for the purpose of this PhD research. At this stage in the PhD, the decision was made to assess this particular technology and the market leading technology manufactured by Forensic Technology. The design of the experimental research was at this stage to examine the functionality of each system when the same sample of bullets and cartridge cases had been acquired to demonstrate the differences between systems and to provoke a debate in the community about interoperability between systems. However, before the research could start there were a number of practicalities to address.

The first issue to overcome was that of access to the two systems that were going to be assessed. Access to one of the systems was less problematic as the author had access to a full system provided by the manufacturer and an offer was made to train the author in the use of the system. Access to the IBIS system was more problematic. The Forensic Science Service (FSS) in the United Kingdom had an IBIS Heritage system and in August 2009 the FSS was approached by the author and a meeting was held at Trident Court, Birmingham to discuss the research and potential collaboration. The FSS was also approached to perform the test firing of a selection of weapons. It quickly became apparent that collaborating with the FSS would have financial implications because the organisation expected to be reimbursed for the cost of any involved scientist's time and access to the IBIS system would be problematic as it was still being used for casework at the time. It also became clear that timescales would not be agreeable between the author and the FSS. After the meeting it was decided to pursue alternative avenues to conduct the research.

In August 2009, the author travelled to Wiesbaden, Germany to meet Dr Walter Wenz - head of the Firearms Section at the German Federal Police (BKA) at that time. Dr Wenz was also at the time the Chairman of the European Network of Forensic Science Institutes Firearms Working Group (ENFSI FWG). The ENFSI Firearms Working Group is the group for ballistics experts in Europe and conducts research in many areas of ballistics science. The author presented the research idea to Dr Wenz and as a result was invited to the ENFSI Firearms Working Group Steering Group meeting in September 2009 to present the research and to request collaboration. This group is responsible for policy matters and the organisation of the annual conference. As a result of this presentation, Dr Wenz with the backing of the ENFSI Firearms Working Group offered to collaborate with the research by coordinating the test firing of weapons. These test fires were to be performed by ENFSI laboratories across Europe and the bullets and cartridge cases sent to Dr Wenz in Germany. The advantage of this was that a large sample of bullets and cartridge cases could be generated. No single laboratory had sufficient weapons of the same type to be viable for the experiment but collaboration with ENFSI resulted in weapons from multiple laboratories being utilised. The second advantage to collaboration with ENFSI was the offer of a dedicated laboratory within the BKA Firearms Unit where the different technologies could be installed and the experiment performed. This collaboration also resulted in the aim of getting all of the manufacturers globally to participate rather than just one of the systems and Forensic Technology. The author was also invited to speak at the 2009 Annual ENFSI Firearms Working Group Conference held in October 2009.

At the annual ENFSI Firearms Working Group conference in October 2009 a meeting was organised by the author. It was known prior to the event that all of the ballistics analysis technology manufacturers would be in attendance therefore it was decided that it would be ideal if a meeting was held between the author, Dr Walter Wenz and the manufacturers. As far as it is known, this is the first time that such a meeting has ever taken place. The purpose of the meeting was to explain the proposed research to the manufacturers, address any concerns and prompt a debate on interoperability between systems. The meeting was also useful in gauging the extent of potential cooperation from the manufacturers.

As previously noted the author was invited to speak at the conference and presented the methodology of the experiment to the forensic experts gathered at the conference for two purposes. Firstly to gain support for collecting a large sample of ammunition that could be used for the experiment. The details of this sample are discussed later in this chapter. The second purpose was to explain the process, aims and objectives to the manufacturers. The day before the author's presentation, a separate meeting was held and all of the manufacturers were in attendance. In this meeting, the purpose of the experiment was explained and there was a discussion between the manufacturers of the aims and likely results. This meeting was critical because it allowed a sense of potential cooperation to be assessed. All of the manufacturers besides one indicated that they would at the very least support the research and at this point in time all except one indicated that they would participate. It was only after this meeting had taken place that the detail of the experimental design could be addressed.

4.2.3 Result of Research at the End of 2009

Despite the fact that at the end of 2009 no experimental research had been conducted there was still considerable research that had been undertaken. Each manufacturer has been visited and a good understanding of the technical principles that underlie each system was gained as well as the countries where each technology is installed. It is noteworthy that the author is likely to be one of very few people globally that has conducted such meetings with all of the ballistics analysis technology providers globally. This is an important outcome of the research. These meetings were crucial to the purpose and scope of the experimental design as well as the likely level of cooperation from the manufacturers, many of whom were concerned about the commercial impact of the proposed research. However at the end of 2009 the majority of the manufacturers were cooperative and clearly understood and supported the aims and objectives of the research. The next section describes the experimental design in detail and provides a systematic description of the decisions made in formulating the experimental design.

4.3 – Experimental Design

4.3.1 Overview of Ballistics Analysis System Workflow

This section presents the experimental design. Before the process and variables are discussed in detail, an overview of the ways in which ballistics analysis systems work and are used is presented to provide context. The workflow is described here and is illustrated in Figure 4-1. Usage of ballistics analysis systems will differ slightly depending on which system is being used. However, the following description covers the necessary steps that are common to the systems examined in this Thesis for both bullets and cartridge cases.

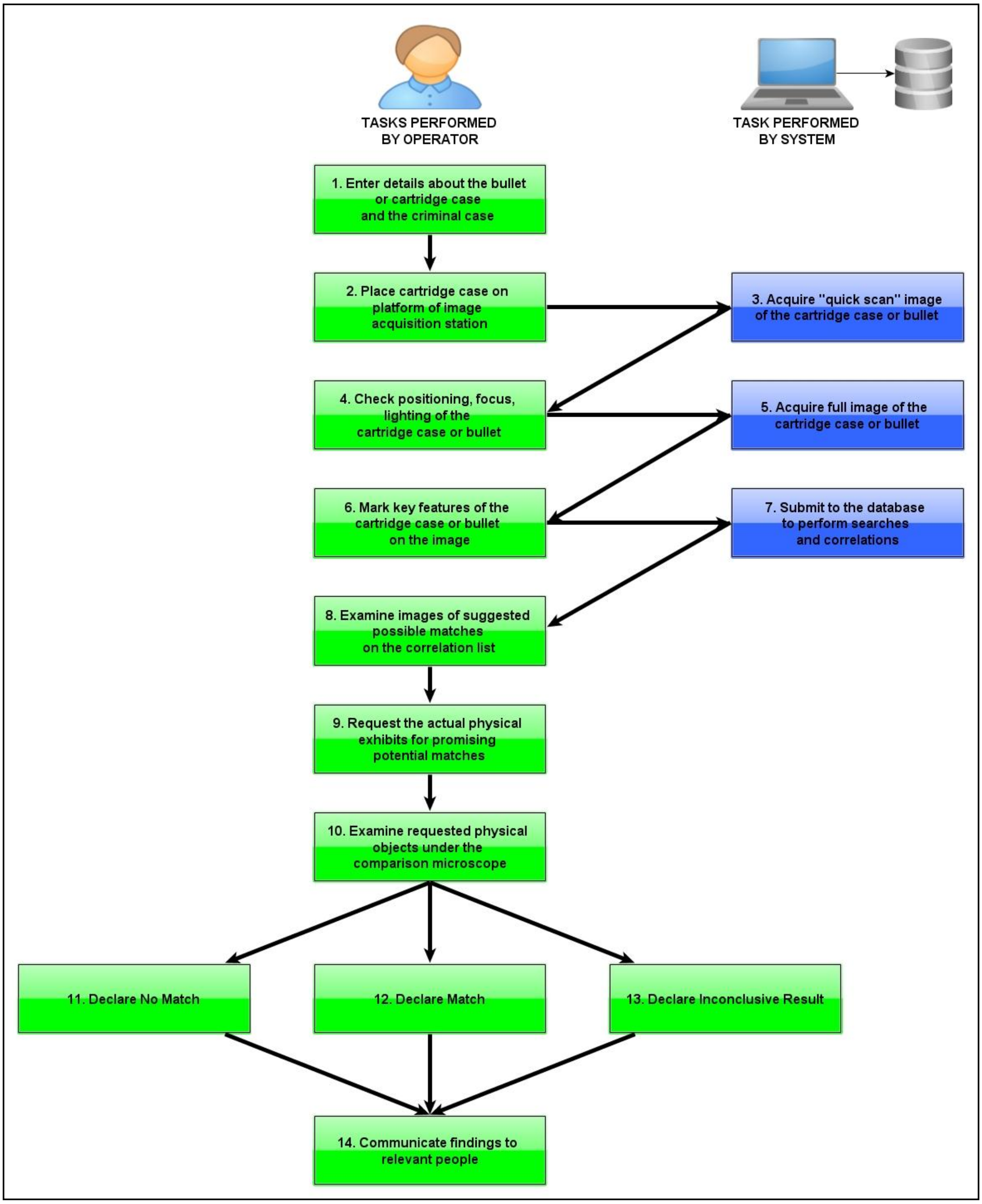
Firstly the object is placed on the platform of the ballistics analysis system ready to be scanned. The object should be placed according to the manufacturers' instructions to ensure the maximum amount of the object surface can be captured. For bullets, some systems used a magnetic platform whilst others use an adhesive surface. Other systems may have a proprietary bullet or cartridge case holder into which the object is placed before being scanned by the system. Depending on the system being used, there will be some data input required. The make, model and calibre of the weapon that fired the bullet are usually entered along with details about the laboratory, operator and the criminal case. The date and time of the scanning is also recorded and is usually automatically generated by the system. Once all the details of the object have been entered an initial "quick scan" is usually performed returning an image of the object to the operator. This allows the positioning, focus, lighting and orientation to be checked before the full acquisition process begins. If the operator is happy with the setup, the acquisition starts. The time taken to acquire a bullet can vary between systems and is dependent on many variables. Examples may be the size and calibre of the bullet and whether or not it is damaged or a fragment of a bullet. The same applies for cartridge cases and a variable that is common to both cartridge cases and bullets and affects acquisition time is the method employed to capture the image. For example, one system may capture multiple images using different lighting angles whilst another system may capture fewer images with fewer lighting angles. A further point of variance is the way in which the bullet images are stitched together as the bullet is rotated and images are captured of the different sections of the surface. This also affects acquisition time. The time taken to acquire an object can vary quite significantly. For example, the time taken for bullet acquisition for BulletTrax 3D is quoted at twenty minutes (Roberge and Beauchamp, 2006) whilst the acquisition time for Evofinder is quoted at three minutes (Evofinder, 2011).

Once the object has been acquired by the system, the operator will be required to highlight distinguishing features on the bullet or cartridge case. Depending on the system, there will be some level of automation. For example, the lands and grooves may automatically be highlighted to the user for bullets but the striations of interest will have to be selected by the user. For cartridge cases, the user may have to select and highlight the breech face impression and the firing pin impression. The key features the user may be required to highlight will be used in the correlation process so it is important that the operator can identify features of interest. Once key features have been marked the bullet or cartridge case image is encoded and entered into the database and correlations are carried out against other objects already stored in the database.

The results of the correlations are provided to the user in the form of a correlation list. This list can be of varying lengths. The correlation lists will have a score associated with each potential match however these scores are not used to determine a successful match or not. A ballistics expert may look at the variance between scores assigned to objects on the same list to prioritise the examination of the images. Usually, the system will allow the expert to view the object in question and each potential match side by side using image processing techniques such as contrast and overlaying to view the images in different ways. Some systems have a “3D” viewing mode that allows the object to be “flipped” to see the lands and grooves in more detail.

If any of the objects on the correlation list look like they might be a potential match, the ballistics examiner will request the actual sample to complete an examination using a comparison microscope. The ballistics expert will then be in a position to declare a match between objects, declare no match between objects or declare an inconclusive result.

Figure 4-1: Ballistics Analysis System Workflow Diagram



4.3.2 High Level Overview of the Experimental Design

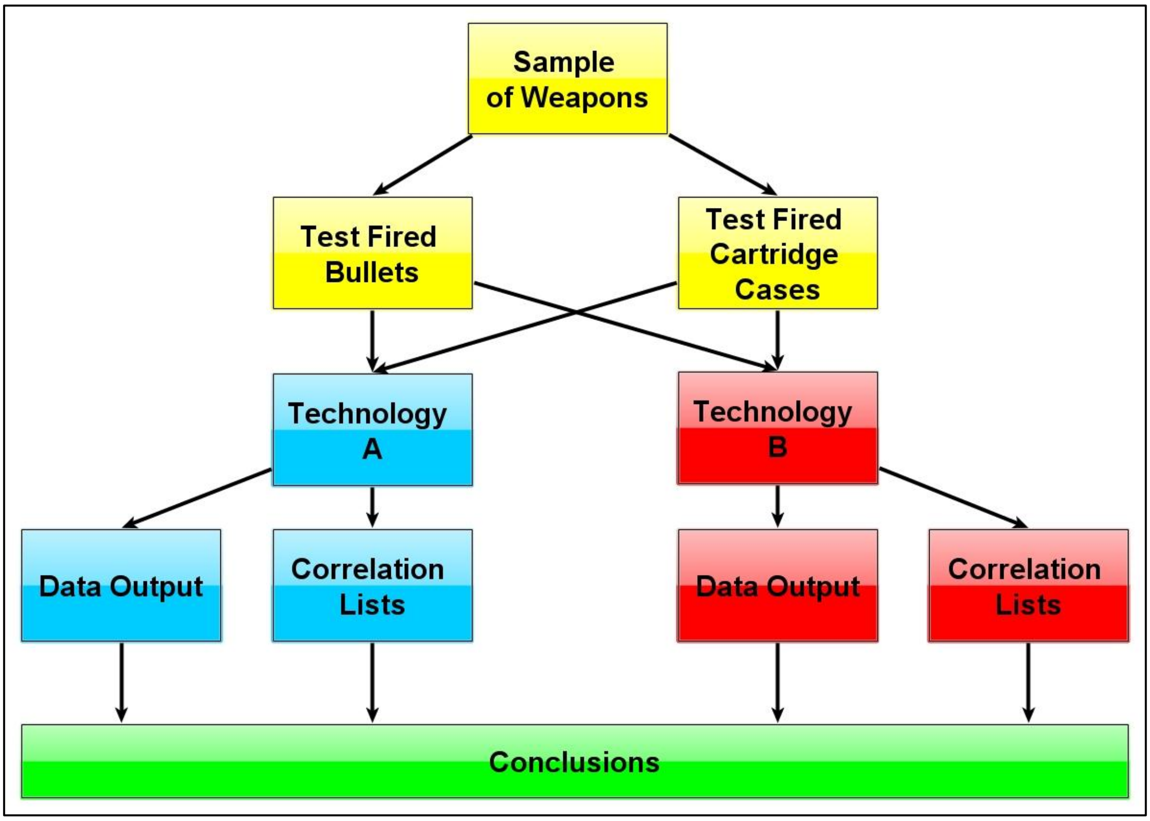
As has been previously discussed, there has never been an experiment conducted with technologies from different providers using the same sample of ammunition. There is also no interoperability between ballistics analysis technologies. Data captured using one technology cannot currently be exchanged or correlated with data that has been captured using another type of technology. The experiment explained in this Thesis was ultimately designed in order to enable a progression toward interoperability and technology integration.

The process involved:

1. The creation of a controlled data set to be used with the different technologies and to provoke a discussion on forensic ballistics standards;
2. The design of a methodology to enable the use of the same data set with different technologies;
3. The undertaking of an experiment with different technologies to prove the feasibility of the methodology and highlight areas for further discussion.

The process involved the input of the same sample of cartridge cases and bullets into two different ballistics analysis systems to enable a representation of the objects to be captured using the different systems. As described in Section two of this chapter, the original aim was to enable all technologies currently available to be assessed as part of this research. However just two of the systems available are included in the experiment that was undertaken. The reasons for this are explained later in this section. This process for assessing two technologies is shown in Figure 4-1. The focus was obtaining the different resulting data because a thorough assessment of the data produced by each system is an essential pre-requisite to any work on interoperability between systems.

Figure 4-2: High Level Overview of the Experimental Process



The experimental part of the Thesis was concerned with an assessment of each technology's work flow, data capture, data generation and data output attributes. In order to design standards and techniques to achieve interoperability there needed to be a thorough understanding of the ways in which each system worked. This section of work also encompassed investigating and documenting the different techniques and scientific principles utilised by each system. Some are based upon digital imaging whilst others use different techniques such as confocal microscopy. The two systems examined for this Thesis are both based on digital imaging. Understanding the similarities and differences between each technique enabled an assessment to be made as to whether or not interoperability would be possible. As part of this process, a detailed understanding was gained of the strengths of each system. It was postulated that each system would operate differently therefore it was logical to assume that each system would have different strengths.

Once the bullets and cartridge cases had been acquired by each system, data was outputted. This data consisted of images and metadata associated with an image. The images themselves were different as were the number of images that were captured. The methods used to capture the images were a differentiating factor as was the resulting metadata associated with each image.

The experimental design explained in detail here has been designed so that the experiment can be repeated as many times as necessary using the same set of ammunition. The test set of ammunition has also been preserved so that the test can be run in the years ahead should any new technologies emerge.

4.3.3 Experimental Design

This section describes the experimental design in detail and the design decisions that were made. It would have been ideal if every single manufacturer that produces ballistics analysis technology took part in the research. At the beginning of the research this was the aim. With this in mind, the manufacturers of each technology were approached. Visits were undertaken to the companies between April 2009 and May 2010 and a series of meetings were held in Wiesbaden, Germany in October 2009 to discuss the experimental approach and these meetings were followed up with a written request to participate and additional telephone calls as necessary.

Eventually due to several difficulties, only two systems were able to be studied as subjects for this Thesis. At this point it should be noted that the market leaders Forensic Technology Inc, manufacturers of the IBIS systems did not take part. The author recognises that this was somewhat limiting to the overall study as much of the previous research work published makes use of the IBIS system but as an overall study the author considered the exercise both in terms of the experimental design and the results produced, as valid and useful to the forensic community.

4.3.4 Location of Research

It was proposed that a dedicated laboratory be used at the Bundeskriminalamt (BKA) in Wiesbaden, Germany and that each company installed their ballistics analysis system in this laboratory for the necessary time it would take to acquire the bullets and cartridge cases for each respective system. A ballistics analysis system consisted of the machine used to acquire the bullets and cartridge cases and the computer attached to the scanner that stored the data, housed the database and carried out the correlations. This approach had numerous advantages. Each manufacturer was asked to provide a system because this would ensure all systems participating were in good working order. Many systems may have been available in laboratories around Europe but using them for the purposes of this experiment would have been impractical because it would have resulted in the systems being unavailable for real casework - a situation which was not acceptable given the large backlogs of work that exist in some laboratories. Use of an already installed system would also result in complications arising from the input of experimental data into a system containing live data. All of these systems require regular maintenance and a criticism that could be directed at the experimental design is that the systems were not calibrated sufficiently. By placing the onus on the manufacturer to provide a system, the responsibility resided with them to provide the system in good working order.

The use of a dedicated laboratory was suggested for a number of reasons. The initial approach was to send the test fired bullets and cartridge cases to the manufacturers. However, previous work that has been carried out in the field of proficiency testing had encountered problems using this approach. Proficiency testing is when test fired objects are examined by ballistics experts to determine the matches and non matches in an experimental sample. Many studies have been halted or left incomplete because test fires have been sent to laboratories and returned damaged or have been lost. To avoid this problem, it was deemed more logical to bring the technology to the test fires especially given the considerable time and effort taken to generate the test data set. Using the laboratory in the BKA also meant that an independent ballistics examiner could oversee the acquisition process in person rather than relying on manufacturers reporting the findings unobserved. This allowed for a greater level of control in the process.

However it was recognised that realistically the only way that the technology could be transported to the BKA laboratory was with the consent and active involvement of the manufacturers. There were many reasons as to why this was the case most notably the cost of transporting the equipment to a different country in all cases by air. It has been recognised, as a result of this work that there might be a situation where there is a requirement from expert users to undertake the test using a system from a manufacturer that declined to participate in the experiment by travelling to the BKA and undertaking the test. Alternatively, it is feasible that with careful consideration and planning the test sample could be transported from the BKA to the laboratory of a user that wishes to undertake the test on a system installed in a working laboratory. However for this happen the benefits of undertaking the test and having the results widely available would have to significantly out weight the risks.

4.3.5 Operator of Each System

Each manufacturer was asked to provide an operator because the level of experience required to operate each system can vary quite dramatically. By asking the manufacturers to provide a suitably qualified operator, the data output should theoretically have been to a high standard and user generated error limited. Early in the process of designing this experiment, consideration was given to using the same person to perform all the inputting of objects. However, it was and still is doubtful that a suitably qualified person exists anywhere in the World due to the number of systems in use in different counties. It is possible that a single person could learn to use each system but it was felt that this may lead to good quality data output on some systems and lesser quality input on other systems. Consideration was also given to the author inputting the data into each system but it was felt that the author should remain impartial throughout the entire process and that by remaining impartial the credibility of the results would be significantly strengthened. In order to control the variables that may have affected this measure, it was decided to ask the manufacturers to provide an operator. The rationale is that these companies know how the technology works intimately and would therefore be able to provide an operator that could get the best possible results out of it.

4.3.6 Obtaining Test Fired Ammunition

In order for the research to be controlled and scientifically valid, a relatively large sample of objects (bullets and cartridge cases) was required from the same make and model of weapon. The author had spoken to a number of firearms experts who recommended the assessment of the systems using ammunition fired from 9mm calibre weapons. The reason for this was that the majority of previous research has been conducted using database of acquired 9mm ammunition. This caused an immediate problem because 9mm handguns are banned in the United Kingdom. In order for a sample of bullets and cartridge cases to be obtained, the police or a forensic laboratory with the authority to carry out test fires would have had to be approached. Even if such an organisation could be found it would have to have a sizable number of weapons in a safe reference collection that were of the same make and model. A safe reference collection refers to firearms that were not in circulation. This avoided any ethical issues with weapons that had been used for illegal purposes. The weapons could also not be weapons legally used by police officers for the same reasons.

As previously detailed, in August 2009 a meeting was held in Wiesbaden, Germany with Dr Walter Wenz who was the then chairman of the European Network of Forensic Science Institutes (ENFSI) Firearms Working Group (FWG). The extent of the research was explained and Dr Wenz offered to collaborate by coordinating the test firings of the sample weapons and also allowing ballistics experts to provide technical assistance. Dr Wenz also offered the use of laboratory facilities at the BKA.

In September 2009, Dr Wenz wrote to members of ENFSI across Europe asking them to provide as many test fires of a particular type of weapon as possible. Some members of ENFSI provided test fires from multiple weapons and some provided test fires from a single weapon with the aim overall of obtaining test fires from 220 weapons. By the end of 2009 test fires had been obtained from 196 weapons and it was felt that this was a sufficiently large sample.

Taking this approach solved many issues. Each person that performed the test fires was a qualified forensic scientist who routinely carried out test fires for the purpose of identifying weapons used in actual crimes. The procedures that are in place in the laboratories where the test fires have taken place are of a very high standard and test fires performed by these examiners are often presented as evidence in court. This adds a high degree of reliability to the test fires that have been provided by the ballistics examiners. On a practical level, the provision of these test fired objects by ENFSI members has meant that the author has not had to either personally perform the test fires or be present whilst they are being carried out meaning that many potentially problematic health, safety and ethical issues have been avoided.

4.3.7 Test Firing Process and Bullet Recovery Method

Bullets were recovered using the following two distinctive techniques:

- Water tank
- Cotton wool

Test firings must be conducted in a controlled environment to eliminate as many extraneous variables as possible. There are differences between the ways in which test firings are carried out between countries. Recovering cartridge cases from test fired weapons is simple; they just have to be picked up and logged. Bullets however are more difficult to recover.

Heard (2008) describes the different techniques that can be used to recover bullets. Cotton or waste wadding can be used but striations can be damaged by the material because it is quite abrasive. High grade, long fibre cotton wool can also be used and is effective at preserving striations on the bullets. The disadvantage to this technique is that the material has to be frequently replaced and is therefore expensive. The alternative method of recovering bullets is to use water tanks but these can also be problematic. Heard (2008) discusses, in detail, the problems inherent with the utilisation of water tanks. Using a horizontal water tank involves firing a bullet at an angle from one end of the tank. Once the bullet enters the water it begins to lose velocity and recovery can therefore be difficult. The formation of algae in the tank can make the water tank an unpleasant environment but this can be tackled by adding chemicals to the water but these chemicals must not affect the markings on the bullets in any way. Test fires must be carried out carefully using horizontal tanks because a shallow shooting angle can result in bullet ricochet and damage to the tank. Similarly a steep angle can also result in the bullet striking the tank and causing damage.

The intricacies involved in controlling the test firing process are important when assessing match probabilities and the strength of the evidence. Often, evidence is presented in court as a match between an object recovered at a crime scene and an object recovered from a test fired weapon. As the method used to recover a test fired bullet can significantly affect the striations imprinted on a bullet, it is important to highlight the different methods of bullet recovery.

The choice of which bullet recovery method to use is also significant depending on the circumstances a particular country or laboratory faces. For example, a laboratory performing relatively few test fires might not need to incur the expense of installing a water tank. Conversely, a laboratory performing many test fires might be economically justified in installing a water tank and the associated reinforcements. In practice, a combination of all methods is used in court when this type of evidence is presented resulting in the need to highlight the benefits, disadvantages and risks associated with each method.

Ideally, the method used to produce test fires would have been the same for all 196 weapons. However this was impractical because many of the laboratories had different equipment installed and a constraint on this would have resulted in a smaller number of weapons being available. It was therefore decided that it was acceptable to compromise on this point and leave the test firing method to the discretion of the forensic scientist performing the test fires. However, the methods chosen were designed not to produce any damage to the bullet striation marks.

4.3.8 Choice of Weapon

All test fires used as part of this experiment had to be from the same make and model of firearm. This is because of the way in which the systems operate and the ways in which distinguishing marks are identified on cartridge cases and bullets. There are two types of markings on bullets and cartridge cases:

1) Individual markings – These marks can identify an object fired by a particular gun and another object fired by the same individual gun.
2) Classmarks – These marks can identify the make and model of weapon that fired the object. Distinguishing marks such as firing pin impressions can be indicative of the make and model of the weapon that fired it.

All of the ballistic systems work in a similar way to generate a shortlist of objects upon which correlations are to be carried out.

1) An operator enters information about the object such as calibre and ammunition type. Information concerning Classmarks is also entered.
2) The system uses this information to trim the database search and generate a shortlist of objects already stored in the database that are to be correlated against the object in question.
3) A set of heuristics are applied in this process. For example a 9mm bullet will never be correlated with a 7.65mm bullet.

For example, if an object in question is known to have been fired by a Beretta 92 which is a 9mm weapon, the shortlist generated by the machine will only contain Beretta 92's and objects which have "unknown" information. A Beretta 92 would not be compared to any other make and model of firearm. The reason for this is that actual correlations of images and binary data about images are computationally intensive and the more correlations performed, the longer it will take to generate a list of results. This rationale is based on the principle that if the make and model of weapon that fired two different objects is different then there is no possibility that the firearms are the same and the objects will therefore not be matched.

The first step in this process whereby a shortlist is generated is carried out using simple Structured Query Language (SQL) queries that operate against whichever Relational Database the manufacturer has chosen to use. The second step of image correlation uses the proprietary methods of the manufacturer.

Weapons of type Beretta 92 were chosen for this experiment for multiple reasons both technical and logistical. Logistically, these weapons were a sensible choice because they are widely distributed in reference collections around Europe. Therefore access to these weapons was relatively easy unlike other rarer firearms. Some firearms have markings that make the objects fired from them highly distinguishable and some firearms have markings that make identification of objects fired from them very difficult. The Beretta 92 contains a complex set of marks but the marks can be identified. The author was also informed by ballistics experts that “hits” have been generated on these systems when the weapon in question is a Beretta 92. A balance needed to be achieved between making the correlations easy for the systems to perform and yet difficult enough to identify differences between the systems. After consultation with ballistics examiners, it was decided that the Beretta 92 would be the weapon of choice. A form was completed for each test fired weapon that provided details on the year of manufacturer and the serial number.

4.3.9 Ammunition Type

9mm parabellum full metal jacket ammunition was used for test fires. Ballistics examiners in Europe were asked where possible to test fire the weapons using two out of the following five brands.

- Fiocchi
- Geco
- S & B
- CBC
- PMC

It would have been ideal if all the test fires were conducted using the same ammunition type. However in practice this was not possible as different laboratories had access to different types of ammunition. Instead it was decided to restrict the ammunition types to five commonly used ammunitions types.

4.3.10 Preparation of Ammunition

All of the bullets were indexed. This involved the inscription of a randomly generated four digit number on each cartridge case and each bullet. This four digit number enabled the known matches and non matches to be identified. The key will be kept confidential to enable future use of this dataset in a controlled manner. All of the cartridge cases and bullets were cleaned using ultrasonic methods. Additionally, ammonia was used to remove the dye on the cartridge cases that the manufacturers had marked them with. The bullets and cartridge cases were placed in groups of three into the ultrasonic bath for two minutes. This process was carried out as per standard operating procedures in the BKA and ensured that distinguishing marks on the ammunition were not obscured by gunshot residue or other dirt.

4.3.11 Sample Size and Construction

The specific details of the bullet sample and the cartridge case sample follow this paragraph. The number of samples in each group for bullets and cartridge cases differed slightly. The sample was designed like this deliberately because when designing the experiment it was decided that a list of 40 object index numbers would be presented to each company and they would then have to decide whether or not the objects had matches in the database. It was decided that it would be preferential to avoid splitting the sample into 20 known matches and 20 known non matches to try and avoid making the split obvious to the companies and to try and prevent the companies "guessing" matches. Instead the decision was made to vary the number of known matches and known non matches slightly to try and control the experiment further. However, once the cartridge cases and bullets had been acquired it was decided that examination of the correlation lists alone would provide sufficient data for analysis so the companies were not asked to declare matches. The sample size had already been decided upon and all objects had already been acquired by the time this decision was made. For both bullets and cartridge cases, it was decided to include objects in the test set of ammunition that had no match in the database (known non matches). The rationale was to examine how each system handled bullets and cartridge cases with no known match in the database. However, the known match sample provided sufficient data for analysis. When this decision was taken, the sample had already been determined and acquired by each system.

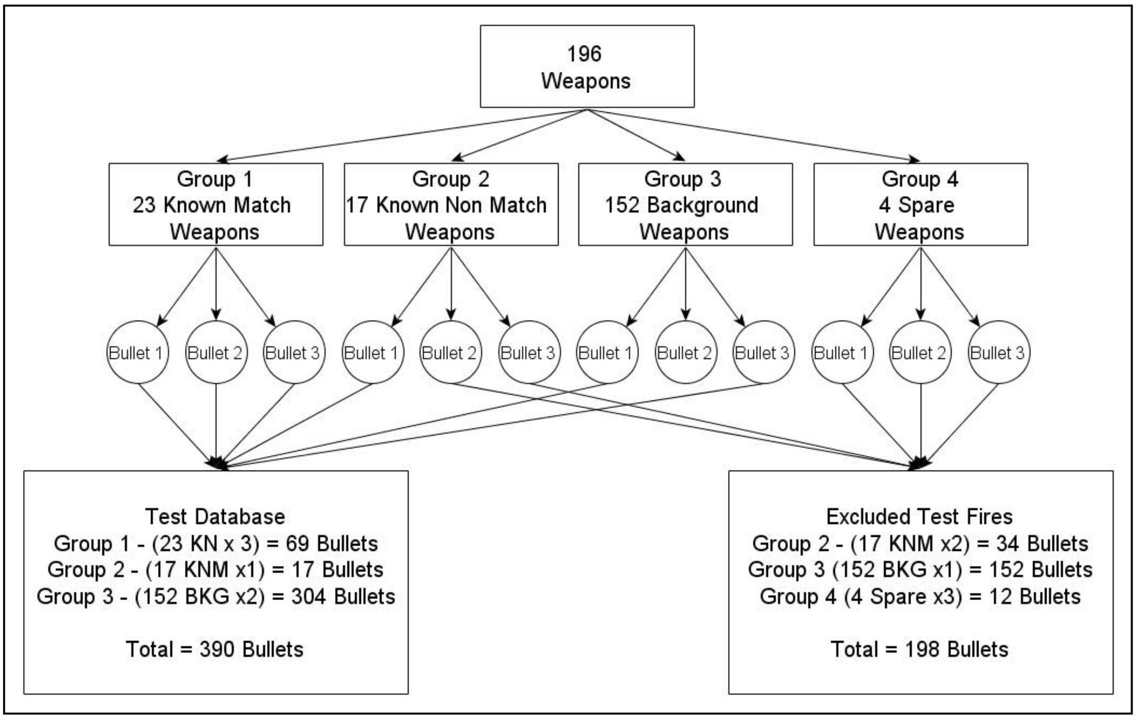
4.3.12 Details of the Bullet Sample

Each of the 196 weapons was test fired three times to produce three bullets. The test fires were then split into four groups. Group 1 consisted of the known match sample. Twenty-three weapons were chosen at random and three test fired bullets from these twenty three weapons formed the known match (KM) sample. All three bullets from these twenty three weapons were acquired by each technology resulting in the known match sample consisting of sixty nine bullets. One of these bullets from each of the twenty three weapons was chosen at random to be the test known match bullet that results would be reported for and the correlation list examined. Group 2 consisted of the known non match sample. Seventeen weapons were chosen at random and one bullet from the seventeen chosen known non match weapons was acquired. Group 3 consisted of the background sample. Two bullets from each of the remaining 152 weapons were inputted onto each system. This resulted in a background sample of 304 bullets. Finally, Group 4 consisted of spare weapons, for which the ammunition was not required for the experimental sample. The test fires from these four spare weapons were not included in the test database. Table 4-4 provides the details of the bullet test database and Figure 4-3 illustrates this.

Table 4-4: Bullet Test Database Metrics

	Number of Weapons	Included Bullets from each weapon	Excluded bullets from each weapon	Total Included Bullets	Total Excluded Bullets	Total Bullets
Group 1 Known Matches	23	x3	x0	69	0	69
Group 2 Known Non Matches	17	x1	x2	17	34	51
Group 3 Background Sample	152	x2	x1	304	152	456
Group 4 Spare	4	x0	x3	0	12	12
Total	196			390	198	588

Figure 4-3: The Bullet Test Database



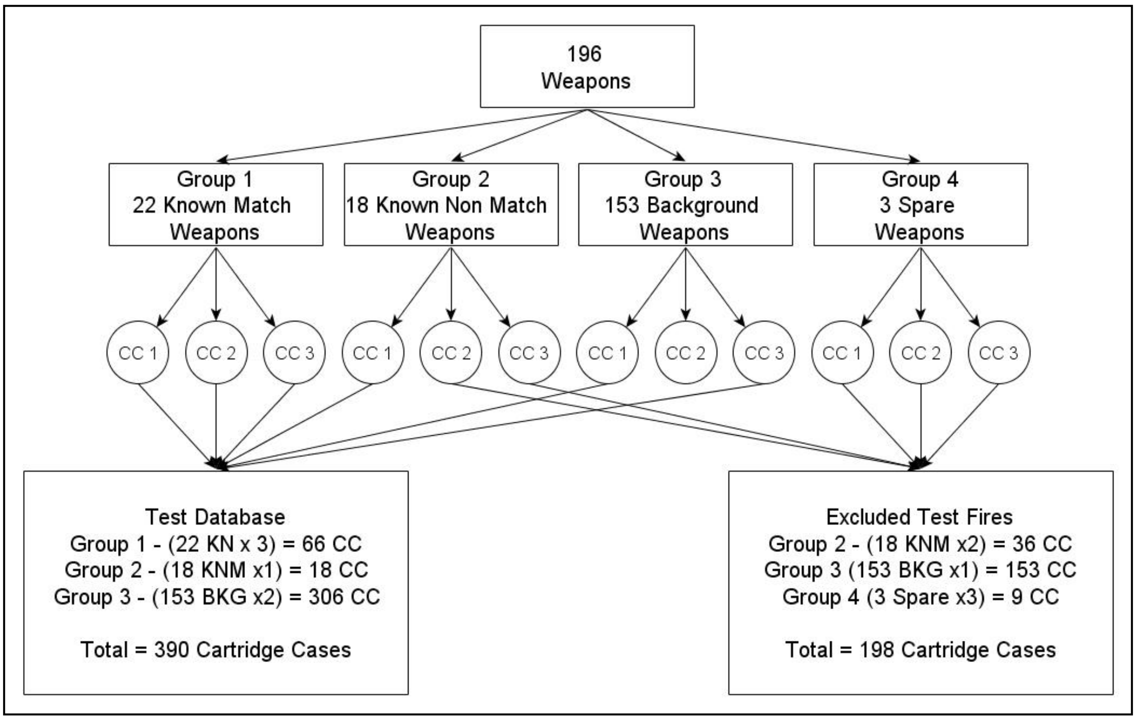
4.3.13 Details of the Cartridge Case Sample

Each of the 196 weapons was test fired three times to produce three cartridge cases. The test fires were then split into four groups. Group 1 consisted of the known match sample. Twenty two weapons were chosen at random and three test fired cartridge cases from these twenty two weapons formed the known match (KM) sample. All three cartridge cases from these twenty two weapons were acquired by each technology resulting in the known match sample consisting of sixty six cartridge cases. One of the cartridge cases from each of the twenty two weapons was chosen at random to be the test known match cartridge case that results would be reported for and the correlation list examined. Group 2 consisted of the known non match sample. Eighteen weapons were chosen at random and one cartridge case from the eighteen chosen known non match weapons was uploaded to the database. Group 3 consisted of the background sample. Two cartridge cases from each of the remaining 153 weapons were inputted onto each system. This resulted in a background sample of 306 cartridge cases. Finally, Group 4 consisted of spare weapons. The test fires from these three spare weapons were not included in the test database. Table 4-5 provides the details of the cartridge case test database and Figure 4-4 illustrates this.

Table 4-5: Cartridge Case Test Database Metrics

	Number of Weapons	Included CC from each weapon	Excluded CC from each weapon	Total Included CC	Total Excluded CC	Total CC
Group 1 Known Matches	22	x3	x0	66	0	66
Group 2 Known Non Matches	18	x1	x2	18	36	54
Group 3 Background Sample	153	x2	x1	306	153	459
Group 4 Spare	3	x0	x3	0	9	9
Total	196			390	198	588

Figure 4-4: Illustration of Cartridge Case Test Database



4.3.14 Delivery of Results

Each company was asked to ensure that all 390 bullets were correlated against everything in the database and that all 390 cartridge cases were correlated against everything in the database. This resulted in each company producing correlation lists for 390 bullets and 390 cartridge cases. Once these correlation lists had been received, the correlation lists for the twenty three test bullets and twenty two test cartridge cases were examined by the author and this enabled the results to be analysed.

4.3.15 Application of the Results to Wider Policing Issues

In addition to the experimental research already described, the results were interpreted in the context of some of the wider policing issues relating to gun crime. The literature review explained the nature of gun crime, the problems caused to the police by gun crime and the difficulties inherent in preventing and detecting gun crime offences. Part of the methodology of this Thesis was the interpretation of the experimental results in light of some of these issues. Once the results were analysed and discussed in isolation, they were discussed in the context of research that has previously been carried out with ballistics analysis systems. The results were then interpreted and discussed in the context of wider policing issues relating to gun crime. One of the gaps identified in the literature review was the lack of multidisciplinary research that addresses gun crime from different perspectives. It was described how there is a lack of research that combines work in the forensic ballistics arena with other work in the criminology domain. A discussion of the experimental research in this Thesis addresses this gap by applying the results gained to wider policing problems specific to gun crime with the aim of generating new knowledge and approaches. The impact and implications of the results both positive and negative, on the police investigation of gun crime were discussed.

The results of the experimental work are presented in the next Chapter.

Chapter 5 – Results and Discussion

5.1 – Results

5.1.1 Introduction

Recent times have seen the increasing use of ballistics analysis systems to facilitate the investigations of crimes involving firearms. Alongside the use of the systems, research and development has occurred. This has taken the form of research concerning the functionality and performance of ballistics analysis systems or the examination of alternative techniques to examine bullets and cartridge cases. The work of Tulleners (2001), De Kinder, Tulleners and Thiebaut (2004), George (2004a and 2004b), Nennsteil and Rahm (2006a and 2006b) and Brinck (2008), has led to an understanding of the capabilities of the IBIS suite of products whilst work such as that of Braga and Pierce (2004) has also led to an understanding of the impact ballistics analysis systems can have on the experts that use them and police investigations. The work of Xie et al (2009) and Barrett Tajbakhsh and Warren (2011) has described how new techniques can be applied to forensic ballistics.

The literature review highlighted problems specific to crimes involving firearms. These problems included the reluctance of victims and witnesses to talk to police and the fact that often there is very little evidence available. This results in a situation whereby if ballistics evidence is available in the form of a bullet, cartridge case or a recovered firearm it can be the only evidence available. As such it becomes a significant part of the police investigation. In the forensic ballistics arena, ballistics analysis systems play a major role which can potentially reveal previously unknown links to other crimes.

When this Thesis commenced there had been no research conducted on systems other than the IBIS Heritage and IBISTRAX 3D systems despite the fact that alternative systems were and continue to be installed in many countries and laboratories. There was also no interoperability between systems. Data could not be exchanged between systems produced by different manufacturers. Furthermore, there had been no work conducted to examine the possibility of interoperable systems or to lay the groundwork for any progress to be made towards interoperable systems. It is argued throughout this Thesis that the only way to progress towards interoperable systems is to gain a thorough understanding of the ways in which the different systems work and the data that is produced both in terms of the images and the accompanying data about the objects. With this phase of work complete, an assessment can at least be made considering the feasibility of interoperability and the extent to which it may be possible. With this is mind, the work in this Thesis focused on the design of an experiment to enable the same sample of bullets and cartridge cases to be inputted into two different systems to enable the similarities and differences between the systems and data to be observed and documented for the purposes of informing a debate on the potential for interoperable systems. The contributions to knowledge of the Thesis have been the production of a test set of ammunition, the design of a methodology and the application of the test set and methodology to examine two different systems. This Chapter presents the results of the experimental research and discusses the results in the context of previous work. This is both in terms of forensic ballistics and wider policing issues relevant to gun crime.

5.1.2 Structure of the Results Chapter

The previous Chapter explained the rationale of designing and undertaking experimental research with automated ballistics analysis systems. The previous Chapter also explained in detail the experimental design. This Chapter describes the results that were obtained from the experimental research. The current section (5.1) serves as an introduction, placing the results in context and explaining some of the key points and principles which underpin the results. Section 5.2 describes the bullet results and section 5.3 describes the cartridge case results. A discussion is conducted in section 5.4 on the definition of an error rate for ballistics analysis systems using the current results.

5.1.3 Explanation of Key Points

On completion of the experiment, each company that participated delivered the results which consisted of the correlation lists and scores for each of the 390 bullets and 390 cartridge cases. The results were delivered as either an excel file or a CSV[14] file. Each bullet and cartridge case was inscribed with a four digit index number that allowed the matches and non matches to be clearly identified but also allowed the sample to be randomised. The results consisted of a correlation list for each of the 390 bullets and 390 cartridge cases and each correlation list could be identified and attributed to a bullet or cartridge case by the four digit index number. The correlation lists for the predetermined test objects (23 bullets and 22 cartridge cases) were then examined to ascertain where the two known matches were ranked.

Each system correlates a questioned object with the other objects in the database and generates a correlation score for the comparison of the two objects. This score is then used to generate a correlation list where objects are ranked for similarity based on the correlation scores. For example consider test bullet A. This bullet is correlated separately with bullets B, C and D in the database.

When bullet A is compared and correlated with each bullet the following scores are generated:

- Bullet A compared to Bullet B = 0.567
- Bullet A compared to Bullet C = 0.678
- Bullet A compared to Bullet D = 0.234

[14] CSV stands for comma separated value. This is a text based file that can be imported into Excel.

Therefore, the correlation list for bullet A would be generated using the above scores to rank the bullets in order of similarity to bullet A and would be as follows:

Table 5-1: Bullet A Correlation List (Example)

Correlation List Position	**Object**	**Score**
1	C	0.678
2	B	0.567
3	D	0.234

Once bullet A has been compared to the other bullets in the database, the process would be repeated for bullet B, then for bullet C and finally for bullet D allowing four separate correlation lists to be generated – one for bullet A, bullet B, bullet C and bullet D. It should be noted that the correlation scores presented by the systems are not traditional correlation coefficients and they are not measures of statistical significance. They are scores generated by the proprietary algorithms of each system and therefore can only be considered in the context of the system that generated the score. This point is made by Cork et al (2008:126) albeit referring to the IBIS Heritage system:

> *"The second basic flaw is the use of the term "correlation" to describe the IBIS comparison process, which imputes to the system an unjustified air of technical exactness. The common, statistical use of the term implies a particular type of relationship and quantifies the strength of that relationship. In comparison, IBIS scores are described by the system's own training materials as having no intrinsic value, severely limiting the ability to express the strength of similarity between two exhibits and to compare results across different runs of the system."*

The only point of known similarity between the systems examined in this Thesis concerns the range of the scores. Each system generates correlation scores in the range of 0 to 1 where a score of 1 would represent a greater similarity than a score of 0. Although bullets have been used to explain the correlation list generation procedure above, the same procedure also applies to cartridge cases. It is for the above reasons that the correlation scores are not considered but instead the correlation list positions are used for analysis. The correlation scores can be found for all the test bullets and cartridge cases in Appendix one.

There were twenty three bullets selected to be test bullets and twenty two cartridge cases selected to be test cartridge cases. The four digit index number for each of the twenty three bullets and twenty two cartridge cases was used to identify the correlation list of each object. The two known matches in the database for each of the test objects can also be identified by a four digit index number and it was this number that identified the object on each correlation list. Because the four digit index numbers can be used to identify the objects, the matches and the non matches in the database, they are not used in the presentation and discussion of the results. Instead, each test bullet or cartridge case is labelled with a number (1 to 23 for bullets and 1 to 22 for cartridge cases) and the post-fix A. The two known matches are labelled with the same number and the post-fix B and C respectively.

On receipt of the results, the correlation lists for each of the twenty three cartridge cases and twenty two bullets were examined to ascertain the positions on the correlation lists of the two known matches for each bullet or cartridge case. The correlation lists for each of the two different systems were examined to enable the correlation lists to be compared for the same object for each different system. The two companies that participated in the experiment did so under a confidentiality agreement therefore the systems are not identified and are instead referred to as system A and system B.

5.1.4 Potential for Statistical Analysis of the Results

Consideration was given to carrying out statistics analyses on the results generated by each system. One considered measure was a Pearson's rank order correlation analysis. A Pearson's correlation coefficient is a measure of the strength of the relationship between two variables. Consideration was given to undertaking analysis of the correlation list positions and correlation scores of the highest known match for each of the test objects to ascertain whether or not there was a statistically significant relationship between correlation list position and correlation scores for known match objects.

However after careful consideration it was thought that this was not appropriate and could generate potentially misleading results for the following reasons. The first relates to the ways in which the systems work and the correlation scores that are generated by each system. It was described above how the correlations scores generated by each system are not traditional correlation coefficients but are generated by proprietary algorithms to each system. Cork et al (2008) implied that the use of the term correlation is somewhat misleading. Instead the correlation scores should be considered more as similarity score between two objects generated for the sole purpose of ranking objects for relative similarity. Consequently, the correlation scores cannot be compared between systems. A further point is that each correlation score is only relative to the current questioned object. For example, consider object 1A that has a match in the database (object 1B). The correlation algorithm generates a score of 0.513 and this places object 5B at position 1 on the correlation list as the correlation procedure has not rated any other objects as being more similar. Now consider object 2A which has a further match (2B) in the database. The correlation procedure generates a correlation score of 0.634 and places object 2B at position 2 as there was an additional non matching object that the correlation procedure scored more highly. This shows that the generated correlation scores are only relative to the questioned object and should not be compared between objects in the same system. This undermines the case for conducting statistical analyses on the correlation scores even within the same system. The fact that the integrity of the generated correlation scores is low and is recognised as such by users and the manufacturers again undermines the case for conducting statistical analyses.

The second reason for not conducting statistical analyses relates to the ways in which the systems are used and research that has previously been conducted. Research conducted previously examining more than one system (Brinck, 2008) did not include any statistical analysis of generated correlation scores for the reasons described above. Correlation list positions and percentage success rates have been the chosen medium by which the results have been communicated to the ballistics community for the reason that this way of describing the results is clearly understood. Reporting the correlation list positions and percentage success rates for an experiment that is clearly described is an objective way of reporting the experience of using a particular system. There is also widespread reluctance by users of these systems to attach any significance to the correlation scores. It is for this reason that measures of statistical significance were through inappropriate as the lack of coherence of the correlation scores is widely recognised.

If Pearson's correlation coefficient was calculated, any conclusions drawn from this measure of statistical significance would be severely hindered by the fact that the correlation algorithms that generate the scores are proprietary methods that were not shared with the author or indeed with any other party. Any conclusions would have been affected by the fact that no comment could be made on the methods utilised to generate the scores therefore any conclusion would be affected by a high level of uncertainty and speculation.

It was also felt that reporting of the correlation list positions, percentage success rates and percentage error rates in a similar fashion to previous research would provide ample discussion points. Reporting the percentage success rates has also allowed the current results to be compared to results from previous research. This follows in sections 5.2.4 and 5.3.4.

5.1.5 Explanation of terms used

Throughout this chapter the term "perfect result" is used. This refers to a result where the two matching objects to the test object were correlated at positions one and two.

Throughout this Chapter the term "opposite result" is also used. This refers to a result where one of the systems has correlated the two matching objects in one particular order whilst the other system has correlated the same objects in the opposite relative order. Consider the following example for bullet AA. Bullet AA has two known matches in the database (bullet BB and bullet CC). System A may have correlated matching bullet BB at position 1 above matching bullet CC in position 2. System B however has correlated bullet BB at position 2 below bullet CC at position 1. Table 5-2 shows the two example correlation lists and demonstrates the opposite relative order that the bullets have been correlated in by each system.

Table 5-2: Example Correlation Lists for Example Bullet AA to Demonstrate Use of the Term "Opposite Order".

Correlation List Position	**System A**	**System B**
1	**Bullet BB**	**Bullet CC**
2	**Bullet CC**	**Bullet BB**
3	Other non-match bullet	Other non-match bullet
4	Other non-match bullet	Other non-match bullet
n	Other non-match bullet	Other non-match bullet

The results for the bullets and cartridge cases are discussed separately. Whilst there are common findings between the bullet and cartridge case results, the different nature of the objects and the intricacies in the data acquisition and correlation procedures necessitated separate discussion. Separate discussion was also thought necessary as some laboratories will primarily focus on bullet examinations rather than cartridge case examinations and vice versa. Separating bullets and cartridge cases allows greater specificity and avoids generalisations.

5.2 – Bullet Results

Table 5-3 shows the results for the bullet analysis condition and is the basis for the discussions in this chapter. This table shows the correlation list positions for both known matching bullets for both system A and system B. Where there is no correlation list position given, this means the system did not correlate the matching bullets on the correlation list. The full results including a description of the results for each individual test bullet can be found in Appendix one.

Table 5-3: Bullet Results Matrix

		KNOWN MATCH 1			KNOWN MATCH 2		
	Test Index	Known Match Object (1)	System A Position (KM1)	System B Position (KM2)	Known Match Object (2)	System A Position (KM2)	System B Position (KM2)
1	1A	1B	1	1	1C	2	
2	2A	2B	2	1	2C	1	8
3	3A	3B	1	2	3C	2	1
4	4A	4B	2	1	4C	1	2
5	5A	5B	1	1	5C	2	2
6	6A	6B	2	2	6C	1	1
7	7A	7B	1	1	7C	2	
8	8A	8B	2	2	8C	1	1
9	9A	9B	1	1	9C	2	2
10	10A	10B			10C		
11	11A	11B	1	1	11C	2	2
12	12A	12B	1		12C	17	
13	13A	13B	1		13C	2	3
14	14A	14B	1		14C	2	8
15	15A	15B	2		15C	20	
16	16A	16B	1	1	16C	2	2
17	17A	17B	57		17C	107	
18	18A	18B	1	1	18C	2	2
19	19A	19B	1		19C	6	
20	20A	20B	78		20C		
21	21A	21B	6		21C	11	10
22	22A	22B	2	2	22C	1	1
23	23A	23B	1		23C	37	

The results in Table 5-3 can be used to discuss a range of issues relevant to ballistics analysis systems when correlating bullets. These are discussed below. Some of these concern the performance of the systems, whilst others concern the interaction between the systems and the users. The first two topics discussed are the results that demonstrate agreement and disagreement between the two systems.

5.2.1 Bullets - Agreement between Systems

As previously described, one of the aims of this Thesis was to use the results generated by the systems to inform a debate as to whether or not interoperability between systems is possible. It was argued that a prerequisite for interoperability is an understanding of the ways in which the systems work and the data they produce. The extent to which there is agreement between the systems is one way of assessing the data produced by the systems in the context of potential interoperability. If there are some forms of agreement between the results produced by the systems then this is a favourable result in terms of interoperable systems. If however, there is clear disagreement between the systems, then this could point towards the difficulties of implementing interoperable systems and perhaps suggest that interoperability is not possible.

The results obtained for the two systems for bullets highlight some important points relating to this. The results show that the systems are capable of producing identical results in terms of correlation list positions. Table 5-3 shows complete agreement between the systems for bullets 5A, 6A, 8A, 9A, 11A, 16A, 18A and 22A. Both systems found both known matches in the top two positions and both known matches were found in the same positions for both systems. There was also agreement between the systems for object 10A because neither system found the matching bullets or produced a correlation list. This suggests that there are common features and functionalities between system A and system B when capturing and correlating bullets that would support the case for interoperable systems.

5.2.2 Bullets - Disagreement between Systems

As previously noted, the extent to which there is agreement between the systems is an important variable when considering the extent to which interoperable systems may be possible. Agreement thus far has referred to the systems correlating the same bullets in the exact same positions on the correlation lists. Just as important for informing the debate on interoperability is the extent to which there is clear disagreement between the systems.

Table 5-3 shows that there are occasions (results for bullets 2A, 3A, 4A, 13A, 14A and 21A) where there is clear disagreement between the systems. The results are inconsistent and suggest that the systems are working in different ways. Taking the result for bullet 2A demonstrates this point.

System A has correlated bullet 2B in position 2 and bullet 2C in position 1. System B however has correlated bullet 2B in position 1 and bullet 2C in position 8. If the correlation and ranking of the objects was only determined by the quality of marks and ammunition type then it would be expected that the systems would perform consistently in relation to the ranking of the bullets. This means that it would be expected that regardless of the actual correlation list position the consistent result would be that bullet B was correlated higher than bullet C for both systems. However the results for bullets 2A, 3A, 4A, 13A, 14A and 21A have shown that this is not the case. This demonstrates that there may be an interaction between the key variables of ammunition type, quality of the striations on the bullet, data acquisition procedures and correlation procedures. It is suggestive of these variables affecting the results generated by each system.

5.2.3 Bullet Accuracy – Success Rate Scores

The term "accuracy" can be used to describe many of the results obtained through examination of the systems. For coherence, different types of accuracy are discussed here. In this section, the accuracy in terms of success rate of the systems is analysed. This refers to the percentage of occasions where a bullet or bullets was found on correlation lists of varying lengths. The results presented in Table 5-3 were used to calculate percentage success rate scores. The correlation lists were examined for each test bullet to ascertain the position of the highest placed bullet out of the two known matches. This was used to calculate the percentage success rate that is subsequently referred to as correlating one out of the two known matches.

Table 5-4 shows the percentage success rate for the highest placed known match for bullets on correlation lists of varying lengths. It should be noted that there will be occasions where the second matching bullet has also been correlated in the top twenty. This is discussed below in the section on success rates for finding both known matches. There will also be occasions where the second matching bullet has been correlated outside the top twenty.

Table 5-4: Success Rate Percentage for system A and system B finding 1 Known Match and Correlation List Length

Correlation List Length	System A %	System B %
Top 1	78.26%	56.52%
Top 3	82.61%	60.87%
Top 5	82.61%	60.87%
Top 10	86.96%	69.56%
Top 20	86.96%	69.56%

Table 5-4 suggests that overall system A performed better with a success rate percentage of 78.26% for finding one of the two objects in the top position compared to 56.52% for system B. The percentage success rate for finding one of the two matches in the top 20 was 86.96% and 69.56% for system A and System B respectively. Interestingly both systems display no difference in success rate for correlation lists of ten objects in length or twenty objects in length when finding one of the two known matches. This finding is discussed later in this Chapter in the section on correlation list lengths. Figure 5-1 below shows the result presented in Table 5-4 and allows the differences and similarities between the systems to be observed. This graph clearly shows that for both systems percentage success rate increased as correlation list length increased but only up to correlation lists with ten bullets. There was no increase in performance to be gained by increasing the correlation list length to twenty bullets.

Figure 5-1: Comparison of System A and System B Success Rate finding 1 Known Match and Correlation List Length

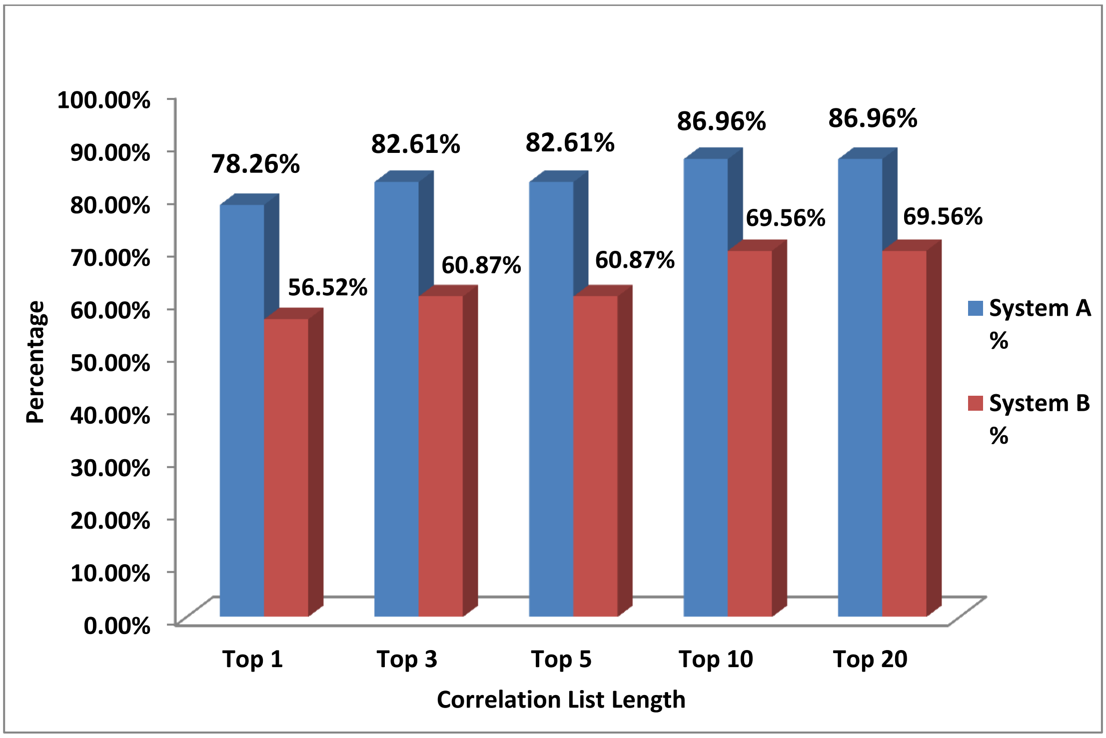


Table 5-5: Success Rate Percentage for system A and system B finding Both Known Matches and Correlation List Length

Correlation List Length	System A %	System B %
Top 2	65.22%	43.48%
Top 3	65.22%	43.48%
Top 5	65.22%	43.48%
Top 10	69.57%	47.83%
Top 20	82.61%	47.83%

Table 5-5 compares the success rate percentage for system A and B when finding both known match bullets on correlation lists of varying lists. This table suggests that overall system A performed better with a success rate percentage of 65.22% for finding both bullets in the top 2 positions compared to 43.38% for system B. The percentage success rate for both known matches in the top 20 was 82.61% and 47.83% for system A and system B respectively.

Figure 5-2: Comparison of system A and system B Success Rate finding Both Known Matches and Correlation List Length

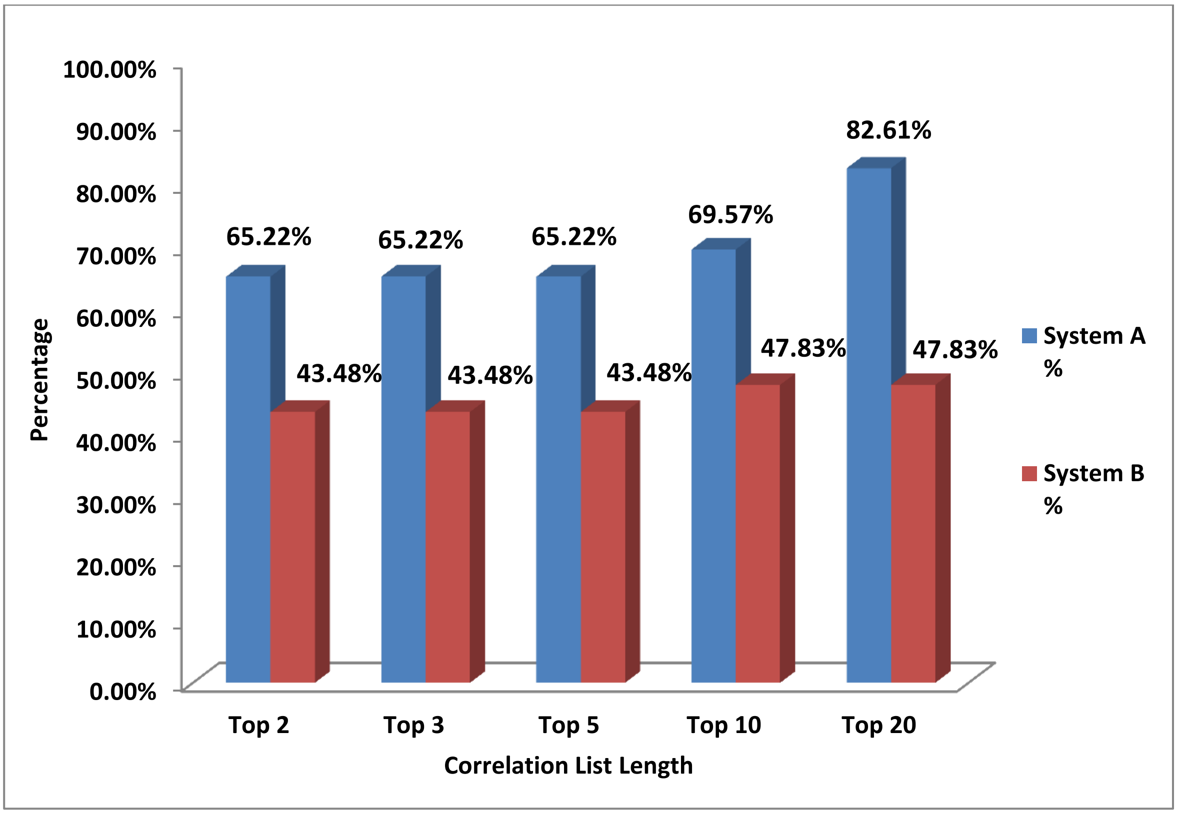


Figure 5-2 visualises the results presented in Table 5-5 and shows that for both systems the success rate for finding both bullets stays the same for correlation lists that are two, three and five bullets in length. The success rate for system A rises to 69.57% for a correlation list of ten bullets compared to a success rate of 47.83% for system B. For a correlation list of twenty bullets the success rate for system A rises sharply to 82.61% whilst remaining at 47.83% for system B. This result has implications for the recommended correlation list length and is discussed in a later section of this Chapter. The next section of this chapter discusses the results in the context of research that has been conducted with the bullet correlation functionality of ballistics analysis systems.

5.2.4 Bullet Accuracy - Comparison with Previous Research

Brinck (2008) examined the IBIS Heritage system and the IBIS BulletTRAX 3D system with bullets fired from consecutively manufactured barrels. The success rates of systems A and B can be considered alongside the results of Brinck (2008) to assess any significant similarities and differences between IBIS Heritage, IBIS BulletTRAX 3D, system A and system B. Brinck (2008) found that for copper-jacketed bullets IBIS Heritage correlated 90% of the test bullets in the top position. The remaining 10% of bullets were correlated in positions eleven to twenty. The results for BulletTRAX 3D showed that 100% of the test bullets were correlated in the top position. For lead jacketed bullets, IBIS Heritage correlated 30% of test bullets in the top ten positions with the remaining 70% falling outside the top twenty. The results for BulletTRAX 3D showed that 70% of test bullets were correlated in the top position with the remaining 30% being correlated in the top ten. Unfortunately Brinck (2008) does not provide exact correlation list positions so the results cannot be compared in the exact same way to the present results.

Nennsteil and Rahm (2006b) also conducted research examining the bullet correlation function of IBIS Heritage and quoted a success rate of between 50% and 75% for bullet comparisons. The success rate refers to the percentage of occasions where the match was found in the top five positions. Unfortunately Nennsteil and Rahm (2006b) do not include a breakdown of the exact correlation list positions so the results cannot be compared in exactly the same way. Table 5-6 provides a summary of the current results for system A and system B with the previous work of Nennsteil and Rahm (2006b) and Brinck (2008). It should be noted that the methodologies employed by Nennsteil and Rahm (2006b) and Brinck (2008) were different to the methodology employed here so the results should not be interpreted as a strict comparison. Differentiating variables include the database size and weapon type used by Brinck (2008) and Nennsteil and Rahm (2006b). Other research conducted on IBIS Heritage and IBIS BulletTRAX (Argaman, Shoshani and Hocherman, 2001; Giverts, 2004) does not quote success rate scores and instead focuses on recommendations relating to the usability of the systems.

Table 5-6: Comparison on the results of this Thesis with prior Research

	Success Rate Top 1	Success Rate Top 5	Success Rate Top 10
System A 1 out of 2 Known Matches	78.26%	82.61%	86.96%
System A Both Known Matches (Top 2)	65.22%	65.22%	65.22%
System B 1 out of 2 Known Matches	56.52%	60.87%	60.87%
System B Both Known Matches (Top 2)	43.48%	43.48%	43.48%
IBIS Heritage Copper Jacketed Bullets (Brinck, 2008).	90%		100%
IBIS Heritage Lead Jacketed Bullets (Brinck, 2008)			30%
IBIS Heritage (Nennsteil and Rahm, 2006b)		50% - 75%	
IBIS BulletTRAX 3D Copper Jacketed Bullets (Brinck (2008)	100%		
IBIS BulletTRAX 3D Lead Jacketed Bullets (Brinck, 2008)	70%		100%

5.2.5 Bullet Accuracy – "Miss" Rate

The "Miss" Rate In this Thesis is used to describe those occasions where one or both known matching bullets were correlated outside the top twenty positions on the list or not correlated at all. This terminology is in keeping with previous research (Tulleners, 2001) and the rationale is that these objects would be unlikely to be discovered in real case work so are labelled as a "miss" as opposed to a "hit" where the bullet is actually found. The accuracy of systems in terms of the number of misses is important. Consider a similar application in another area of forensic science, that of DNA identification. If a DNA sample is loaded onto a National DNA database and no matches are returned, then the investigating officer can be confident that there is not a matching sample on the database. A police officer on receipt of a result from a ballistics analysis system that states there are no matches in the database cannot be confident to the same degree as in other areas of forensic science.

Table 5-5 shows that when finding both known matches in the top twenty, system A achieved a success rate percentage of 82.61%. This result reversed shows that on four occasions (17.39%) one or both known matching bullets were correlated outside the top twenty. For three of the test bullets, both known matches were correlated outside the top twenty or not at all (bullets 10A, 17A and 20A). For bullet 23A, one of the two bullets was correlated outsider the top twenty (bullet 23B at position 1 and bullet 23C at position 37). For system B there were twelve occasions where one or both known match bullets were correlated outside the top twenty - 52.17%. Both known match bullets were correlated outside the top twenty or not at all for bullets 10A, 12A, 15A, 17A, 19A, 20A and 23A. One of the two matching bullets was correlated outsider the top twenty for bullets 1A, 7A, 13A, 14A and 21A[15].

The results regarding the miss percentages for systems A and B suggest that it is difficult for a ballistics examiner or police officer to comprehensively and definitively know that there are or are not links to other crimes in the databases of automated ballistics analysis systems. Much of the focus of using ballistics analysis systems to generate leads for police investigations may be to link crimes together through ballistics evidence. It is equally important to definitively know that there are no links to other crimes. Whilst the results for bullets suggest that ballistics analysis systems may reveal previously unknown links to other crimes on some occasions, it cannot be said that they can definitively rule out links to other crimes. Consider the result for both systems for bullet 10A. Neither system has correlated either of the two matching bullets. This may lead a ballistics examiner to report that there are no matches to other ballistics exhibits in the database. This would be a false conclusion. Consider the impact on a police investigation. The worst and incorrect interpretation of this result would be that the weapon involved in a shooting has not been used previously before. The correct interpretation is that there is no evidence in hand to suggest the weapon has been used previously before. There are links in the database but neither system has been able to successfully correlate the matching bullets. There is a subtle but important difference in definitively knowing there is no match is a database compared to assuming there is no match because a match has not been found.

Ballistics analysis systems are used to check for links between crimes based on ballistics evidence. The accuracy of systems both in terms of success rates and miss rates directly affects the success of this approach. A system that is known to be highly accurate will generate higher confidence in the results than a system than is known or thought to be less accurate. The issue is that accuracy levels, resultant confidence levels and the factors that affect accuracy and confidence levels are not widely known or published for the ballistics analysis systems examined in this Thesis. The next section discusses the accuracy of the systems in terms of those occasions where a known non-matching bullet or bullets were presented above the known matching object. An analysis of those occasions where a “false positive” result has been generated are important when assessing the output of the systems.

[15] For test bullet 10A, neither system correlated the two known matching bullets. Neither system produced a correlation list. Therefore this bullet is included in the percentage of occasions where the systems did not correlate the known matches (the “miss” percentage).

5.2.6 Bullet Accuracy – False Positives

The performance of ballistics analysis systems is directly related to policing issues. The time taken by ballistics examiners to produce potential leads, evidence or intelligence can be critical to an investigation. The ballistics analysis systems that are employed impact on this through the accuracy levels and the resultant time that it takes to examine the bullets on the correlation list. Time is often the most critical variable in police investigations and generally, the sooner evidence is available the better. Results where non-matching bullets have been presented in a higher correlation list position than known matching bullets are important. They make the task of the examiner more complex and theoretically their presence may lead a ballistics examiner to reach a false conclusion. The presence of non-matching objects in positions above the actual match may also increase the time it takes for an examiner to find the actual match, effectively creating “noise” in the results. These factors could potentially waste investigation time and create confusion in the investigation if matches were falsely declared based on the correlation list results. Every non-matching bullet that is presented above a known matching bullet has to be considered and discounted before the known matching bullet is found.

Where the result for a test bullet is not a perfect match then by definition, there has been a non-matching bullet or bullets presented as being more similar than the actual known matching bullet or bullets. The results in Table 5-3 show that both systems correlated non-matching bullets in a higher position than the actual matching bullet on multiple occasions. System A correlated non-matching bullets above the actual matching bullets on seven occasions (bullets 12A, 15A, 17A, 19A, 20A 21A and 23A). System B correlated non-matching bullets above the actual matching bullets on 13 occasions (bullets 1A, 2A, 7A, 10A, 12A, 13A, 14A, 15A, 17A, 19A, 20A, 21A and 23A)[16]. These results are used to define an error rate for the systems. This is discussed in a later section of this Chapter.

There is the potential for these results to mislead a firearms examiner into declaring a false positive match. The extent to which this may actually happen is not known. There is an important finding with regards to the number of non-matching bullets ranked higher than the actual matching bullets. Generally system B produces correlation lists smaller in length than system A for bullet correlations. Table 5-7 shows the correlation list lengths for each of the test bullets and a count of the number of non-matching bullets presented in a higher correlation list position than the actual matching bullets. This is referred to as the number of false positives presented by each system.

[16] For bullet 10A neither system correlated the two known matches. However both systems did not produce a correlation list. This means that there were no false positives produced for object 10A because no bullets were correlated at all.

Table 5-7: Correlation List Length and the number of False Positives presented by each system

	Test Index	System A Correlation List Length	System B Correlation List Length	System A Number of False Positives	System B Number of False Positives
1	**1A**	187	17	0	16
2	**2A**	193	8	0	6
3	**3A**	194	22	0	0
4	**4A**	193	46	0	0
5	**5A**	194	34	0	0
6	**6A**	193	6	0	0
7	**7A**	194	14	0	13
8	**8A**	194	38	0	0
9	**9A**	188	12	0	0
10	**10A**	0	0	0	0
11	**11A**	194	25	0	0
12	**12A**	175	1	15	1
13	**13A**	193	9	0	8
14	**14A**	186	15	0	14
15	**15A**	184	11	18	11
16	**16A**	193	23	0	0
17	**17A**	192	4	105	4
18	**18A**	194	25	0	0
19	**19A**	186	3	4	3
20	**20A**	186	10	185	10
21	**21A**	186	17	9	16
22	**22A**	194	12	0	0
23	**23A**	187	10	35	10
				Total = 371	**Total = 112**

Table 5-7 demonstrates that when system A seems to outperform system B in terms of finding the matching bullets, the fact that often the second matching bullet has been correlated by system A at a fairly low position means that the number of higher ranking non-matching objects is greater than those generated by system B which has not correlated the bullet at all. Consider the results for object 17A an extract for which is shown in Table 5-8 and Table 5-9.

Table 5-8: Results for Bullet 17A

	Test Index	Known Match Object (1)	System A Position (KM1)	System B Position (KM2)	Known Match Object (2)	System A Position (KM2)	System B Position (KM2)
17	**17A**	17B	57	No Correlation	17C	107	No Correlation

Table 5-9: Correlation List Length and False Positives for Bullet 17A

	Test Index	System A Correlation List Length	System B Correlation List Length	System A Number of False Positives	System B Number of False Positives
17	**17A**	192	4	105	4

The extract in Table 5-8 shows that system A correlated bullet 17B in position 57 and bullet 17C in position 107. This table also shows that system B correlated neither bullet. Table 5-9 shows system A produced a correlation list for bullet 17A that contained 192 bullets. System B produced a correlation list containing only four bullets. Because the matching bullets were correlated at such low positions by system A, it is unlikely that these matches would be detected. It is likely that a ballistics examiner would examine the top twenty objects to not find a match. Consider the same ballistics examiner using system B. As the correlation list only contains four bullets, they would at most examine four bullets to realise that there was not a match on the correlation list. There is a trade-off between correlating the matching bullets at low positions versus not correlating the bullets at all.

5.2.7 Bullets - Overall Accuracy of the Systems

The results of the experiment have revealed that the systems work differently and produce different results. Although the data acquisition principles are the same (digital camera images) the specifics of the acquisition process such as image resolution, focus, and lighting will presumably differ. Presumably, the data is also treated differently by each system and the correlation algorithms are different. The variance in the results was therefore expected. However, the nature and characteristics of the variance is a discussion point of interest. For the bullet condition the two systems produced an identical result in terms of correlation list positions for 8 out of the 23 test bullets examined (bullets 5A, 6A, 8A, 9A, 11A, 16A, 18A and 22A). Conversely, this result demonstrates that there were fifteen occasions where the systems did not produce identical results. This suggests the systems treat the measured data differently and consequently produce different results.

The results clearly show that neither system is completely accurate (and it should be noted that the manufacturers do not make this claim). Recall that each test bullet had two matches in the database and the results indicate that both systems perform better when finding one out of the two matches rather than both matches. For bullets and finding one out of the two matches in the top twenty, system A achieved a success rate percentage of 86.96% and system B achieved a percentage of 56.52%. Comparing this to the percentage success rates of 65.55% (system A) and 43.48% (system B) when finding both known matches shows the drop in accuracy and clearly demonstrates that in both conditions, bullets that are known not to match are being placed in higher positions on the correlation list that the actual known matching bullets.

The term "perfect result" was coined to represent those occasions where either system correlated both known matches in the top two positions. For the bullet condition, the systems achieved a perfect result on 65.22% (system A) and 43.48% (system B) of occasions. This shows that on 34.78% and 56.52% of occasions respectively the systems did not produce a perfect result. Non-matching bullets were presented to the user in higher positions that known matching objects on multiple occasions. The accuracy of the systems is discussed in terms of error rate calculations in a later section of this Chapter. The next part of this section discusses the different lengths of correlation lists that are examined and uses the evidence generated in this thesis to make practical suggestions.

5.2.8 Bullets – Ammunition Type

The test fired bullets were generated by multiple laboratories by many different individuals. Although, the type of ammunition was specified, when the test fired ammunition was delivered, the bullets were not labelled accordingly. Unlike cartridge cases which have a headstamp identifying the ammunition type, there is no easy way to identify the bullet ammunition type. It was expected that the different types of ammunition would affect the results but it was not possible to examine this variable for bullets. An analysis of the effect of ammunition type on the cartridge case results is conducted in a later section of this Chapter.

5.2.9 Bullets - Correlation List Length

One of the aims of the Thesis was to conduct multidisciplinary research. A further aim was to discuss the results in the context of wider policing issues. One such issue is the impact ballistics analysis systems can have on police investigations of gun crime. There are a number of aspects relating to the ways in which ballistics analysis systems are used that are relevant. The time taken to uncover potential links to other crimes through the use of a ballistics analysis system is an example. As a ballistics expert will have to manually examine a list of potential matches, the capability of ballistics systems to correlate the known matches at high positions on the correlation list is a key finding. There is a trade-off between the number of bullets that need to be examined and the matches that are actually discovered. Knowing the likelihood of a match being discovered given the examination of all bullets on a correlation list of any particular length is important for both ballistics experts and the police.

There are no standards in place to determine what the length of the correlation list should be. The IBIS training manual suggests it should contain ten objects. Other researchers have suggested different lengths. Silverwater and Koffman (2000) suggested it should contain five objects. Nennsteil and Rahm (2006a) suggested the list should contain between five and ten objects. Brinck (2008) considered the top twenty objects on the correlation list. The research conducted here differed slightly as there were two matching objects in the database for each test object meaning that there are two success rate scores, one for finding at least one out of the two known matches and one for finding both known matches. These success rates contribute to the debate on ideal correlation list lengths.

When finding at least one out of the two matching bullets, both systems showed that the percentage success rate increased as the correlation list length increased but only until the correlation list contained ten bullets. After ten bullets there was no increase in performance to be gained by increasing the correlation list to twenty bullets. However, it is of importance to find all the matches that are present in a database. For this reason, when considering the ideal correlation list length, the success rate for finding both known matches must be used. For system B, on 47.83% of occasions both known matches were found in the top ten and this did not improve when increasing the correlation list length to twenty bullets. For system A, a percentage success rate of 69.57% was achieved for a correlation list of ten bullets, improving to 82.61% when the correlation list was extended to contain twenty bullets. A consistent result for systems A and B is that there was no improvement by increasing the correlation list from two bullets (a perfect result) to five bullets. The improvement came when the correlation list was extended to ten bullets for both systems. When attempting to find both known matches, the results suggest that the correlation list should contain ten objects for system B and twenty objects for system A. Table 5-10 shows the suggested lengths of correlation lists to be examined for each system.

Table 5-10: Suggested correlation list length for Bullets based on Experimental Research

	Bullets Both Known Matches
System A	20
System B	10

The next section describes and discusses the results for the Cartridge Case correlations.

5.3 – Cartridge Cases Results

This section contains the cartridge case results. Both system A and system B have two separate algorithms for correlating cartridge cases. One of the algorithms examines the breech face impression and the other examines the firing pin impression. The results for each algorithm are presented separately. Table 5-11 shows the results for the cartridge case breech face impression and shows the correlation list positions for both matching cartridge cases for both System A and System B. Figure 5-3 shows a cartridge case with the breech face impression marked. The full results including a description of the results for each individual test cartridge case can be found in Appendix one.

Figure 5-3: Cartridge Case Head Showing the Breech Face Impression (Area Between the Two Red Circles).

Table 5-11: Cartridge Case Results Matrix (Breech Face Impression)

		KNOWN MATCH 1			KNOWN MATCH 2		
	Test Index	Known Match Object (1)	Sys A P KM1 BF	Sys B P KM1 BF	Known Match Object (2)	Sys A P KM2 BF	Sys B P KM2 BF2
1	1A	1B	1	1	1C	2	2
2	2A	2B	1	1	2C	2	44
3	3A	3B	1	1	3C	2	202
4	4A	4B	34	363	4C	45	33
5	5A	5B	1	13	5C	10	217
6	6A	6B	1	47	6C	95	1
7	7A	7B	2	268	7C	13	109
8	8A	8B	5	220	8C	31	8
9	9A	9B	1	7	9C	4	357
10	10A	10B	2	114	10C	1	1
11	11A	11B	3	1	11C	2	84
12	12A	12B	1	1	12C	2	81
13	13A	13B	1	1	13C	2	197
14	14A	14B	1	9	14C	2	42
15	15A	15B	1	1	15C	2	78
16	16A	16B	2	163	16C	1	223
17	17A	17B	2	2	17C	1	141
18	18A	18B	5	2	18C	139	234
19	19A	19B	116	75	19C	181	277
20	20A	20B	1	1	20C	2	235
21	21A	21B	168	1	21C	1	33
22	22A	22B	157	1	22C	1	28

Table 5-12 shows the results for the cartridge case firing pin impression and is the basis for discussions in this chapter. Table 5-12 shows the correlation list positions for both matching cartridge cases for both System A and System B. Figure 5-4 shows a cartridge case head with the firing pin impression marked. The full results including a description of the results for each individual test cartridge case can be found in Appendix one.

Figure 5-4: Cartridge case Head with Firing Pin impression Marked (Area inside the Red Circle)

Table 5-12: Cartridge Case Results Matrix (Firing Pin Impression)

		KNOWN MATCH 1			KNOWN MATCH 2		
	Test Index	Known Match Object (1)	Sys A P KM1 FP	Sys B P KM1 FP	Known Match Object (2)	Sys A P KM2 FP	Sys B P KM2 FP
1	1A	1B	1	1	1C	183	192
2	2A	2B	3	1	2C	57	166
3	3A	3B	1	1	3C	176	60
4	4A	4B	9	4	4C	1	1
5	5A	5B	98	257	5C	109	212
6	6A	6B	1	1	6C	6	2
7	7A	7B	35	14	7C	23	18
8	8A	8B	74	1	8C	3	48
9	9A	9B	180	3	9C	1	1
10	10A	10B	49	13	10C	1	1
11	11A	11B	1	1	11C	321	335
12	12A	12B	1	1	12C	315	345
13	13A	13B	1	1	13C	221	8
14	14A	14B	1	1	14C	287	359
15	15A	15B	1	1	15C	199	150
16	16A	16B	1	1	16C	2	2
17	17A	17B	2	1	17C	1	10
18	18A	18B	1	8	18C	2	11
19	19A	19B	67	63	19C	41	66
20	20A	20B	1	1	20C	2	2
21	21A	21B	7	2	21C	11	6
22	22A	22B	12	32	22C	82	176

5.3.1 Cartridge Cases – Agreement between Systems

The results generated by system A and system B for the cartridge case breech face correlation algorithm (Table 5-11) show that there is variance between the systems. The systems are capable of producing the same result but this has happened on only one occasion (cartridge case 1A) for the breech face analysis. If a similar correlation list position is considered rather than an exact correlation list position there does not appear to be any further similar results produced suggesting that the result for cartridge case 1A is the exception rather than the rule. For this particular condition, interoperability appears to be a difficult problem to address simply because of the lack of agreement between the systems when correlating cartridge cases using the breech face algorithm.

The results generated by system A and system B for the cartridge case firing pin algorithm (Table 5-12) again show that there is variance between the systems. The results do show that the systems are capable of producing the same results. The same result has been produced (also a perfect result) on two occasions (cartridge cases 16A and 20A). However, if a similar correlation list position is considered rather than an exact correlation list position, it could be considered that there is agreement of sorts between the systems for cartridge cases 1A, 3A, 11A, 12A 14A and 15A. Both systems have correlated the same cartridge case in position one and the other cartridge case much further down the correlation list. Although the correlation list position of the second object cartridge case differs, given the fact that there are obviously different algorithms and techniques applied, the similarity of the results is striking. For test cartridge case 1A, known matching cartridge case 1C has been correlated in position 183 by system A and position 192 by system B. Also consider cartridge case 11A where cartridge case 11C was correlated at position 321 by system A and position 335 by system B. Despite the number of variables involved in the entire process from acquiring the data to calculating the correlation scores there appears to be some underlying consistency between the systems for the firing pin algorithm. There is a clear difference in the results between the systems obtained for the two different cartridge case algorithms. The level of agreement between the systems was greater for the firing pin algorithm than for the breech face algorithm. As the ammunition type was the same for both algorithms, it may be the case that the type of mark has influenced these results. It may be the case that for this particular type of firearm (Beretta 92) the firing pin impression is used by experts for matching ammunition rather than the breech face impression because the markings are of better quality. This would explain the differences in results for the breech face impression where agreement between the systems was less than the firing pin impression results.

5.3.2 Cartridge Cases – Disagreement between Systems

The number of occasions where there was agreement between the systems for the cartridge case breech face results was low. As was the case for the bullet results, there are results that show a clear disagreement between the systems and again suggest the systems are working differently. The results for cartridge cases 21A and 22A (breech face algorithm) are examples. System A has correlated cartridge cases 21C and 22C at position 1 whilst system B has correlated cartridge cases 21B and 22B at position 1 – an opposite result. This type of result was also observed for cartridge cases 4A, 6A, 7A, 8A, and 11A.

This pattern is also observed for the cartridge case firing pin algorithm. The result for cartridge case 17A is an example. System A has achieved a perfect result correlating cartridge case 17C at position 1 and cartridge case 17B at position 2 whereas system B has produced an opposite result correlating cartridge case 17B higher than cartridge case 17C (positions 1 and 10 respectively). This type of result has also been observed for cartridge cases 5A, 7A, 8A, and 19A. This adds strong evidence to the argument that there is an interaction between the marks on the ammunition, the data acquisition techniques utilised by each system and the correlation algorithms employed.

5.3.3 Cartridge Cases Accuracy – Success Rate Scores

As described during the discussion on the bullet results, "accuracy" can be used to describe many of the results obtained through examination of the systems. In this section, the accuracy in terms of success rate of the systems is analysed. This refers to the percentage of occasions where a cartridge case or cartridge cases were found on correlation lists of varying lengths. The correlation list position of the highest placed known match was considered. This was used to calculate the success rate for finding one out of the two matches. It should be noted that there will be some occasions where the second known match was also correlated in the top twenty. This is discussed in a later section. There were also occasions where the second matching bullet was correlated outside the top twenty.

Table 5-13: Success Rate Percentage for Cartridge Cases. System A (Breech Face Impression) and System B (Breech Face Impression) finding 1 Known Match and Correlation List Length

Correlation List Length	System A BF%	System B BF %
Top 1	72.7%	54.55%
Top 3	81.82%	63.64%
Top 5	90.91%	63.64%
Top 10	90.91%	77.27%
Top 20	90.91%	81.82%

Table 5-13 shows the success rate percentages for system A and system B when finding one out of the two known matching cartridge cases on correlation lists of varying lengths for the breech face algorithm. This table shows that system A achieved a success rate of 72.7% when finding one of the two matches in the top positions and system B achieved a success rate of 54.55%. For correlating one out of the two matches within the top twenty, system A achieved a success rate of 90.91% and system B achieved a percentage success rate of 81.82%. Table 5-13 also shows that there was no improvement in success rate beyond a correlation list of five cartridge cases for system A. The accuracy for system B improved as the correlation list length increased to twenty objects. Figure 5-5 illustrates the findings presented in Table 5-13 and allows the differences between the two systems to be clearly observed.

Figure 5-5: Comparison of System A and System B Success Rate for Cartridge Cases (Breech Face Impression) finding 1 Known Match and Correlation List Length

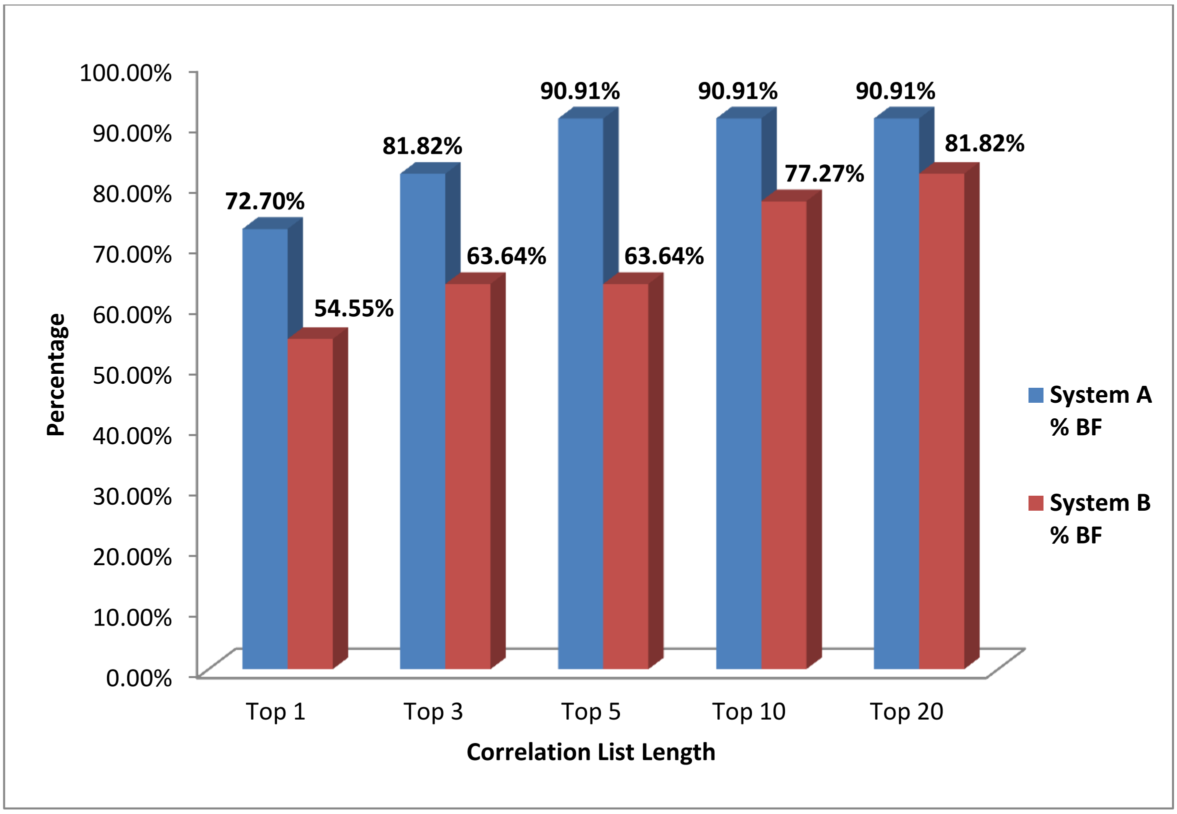


Table 5-14: Success Rate Percentage for Cartridge Cases. System A (Breech Face Impression) and System B (Breech Face Impression) finding Both Known Matches and Correlation List Length

Correlation List Length	System A BF%	System B BF %
Top 2	50%	4.55%
Top 3	54.55%	4.55%
Top 5	59.09%	4.55%
Top 10	63.64%	4.55%
Top 20	68.18%	4.55%

System A achieved a perfect result, correlating both known matches in the top two positions on 50% of occasions. The success rate percentage for system B was 4.55%. When considering the results for finding both matches system A correlated both known matches in the top twenty on 68.18% of occasions and system B on only 4.55% of occasions. This result suggests that the breech face algorithms employed by each system whilst examining the same feature, are different. It also shows that for system B, on the majority of occasions both known matches are not correlated within the top twenty (although one of the two cartridge cases may indeed be in the top twenty). It is possible that the ammunition type affected this result and this is discussed in a later section of this Chapter. Figure 5-6 illustrates Table 5-14 and shows the differences between the systems.

Figure 5-6: Comparison of System A and System B Success Rate for Cartridge Cases (Breech Face Impression) finding Both Known Matches

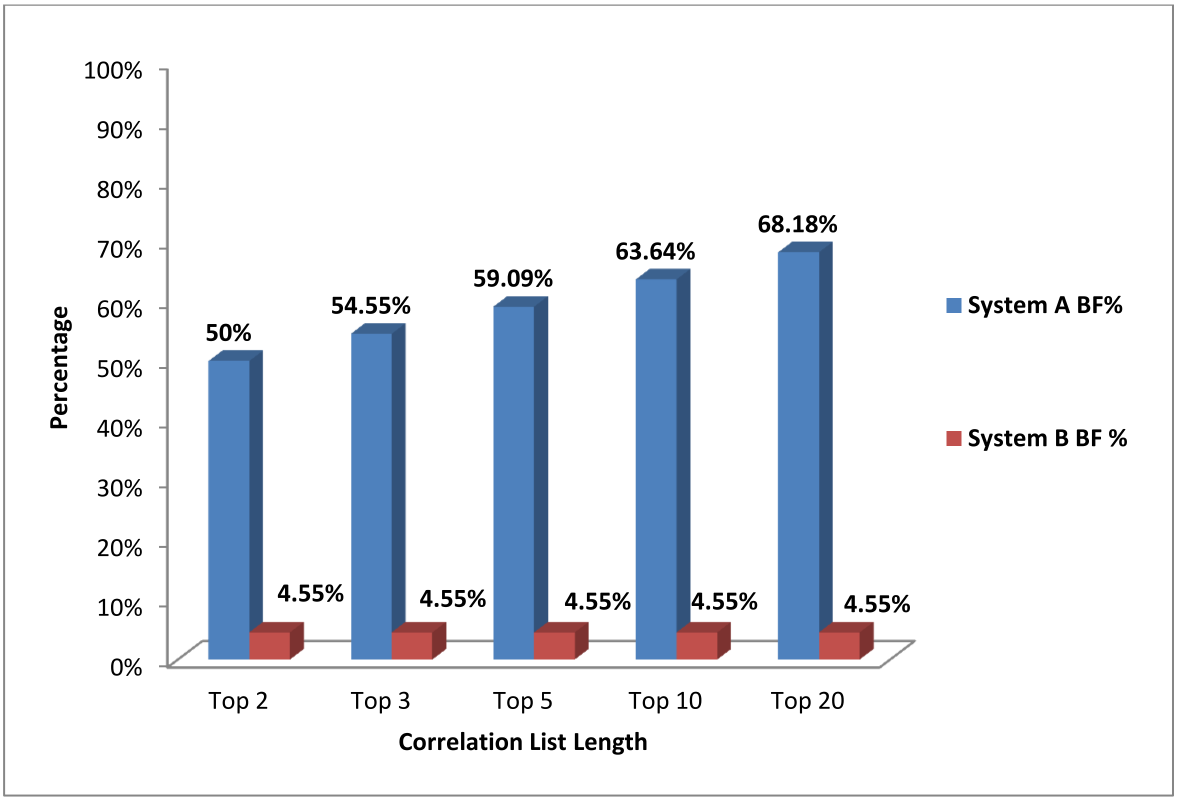


Table 5-15: Success Rate Percentage for Cartridge Cases. System A (Firing Pin Impression) and System B (Firing Pin Impression) finding 1 Known Match and Correlation List Length

Correlation List Length	System A FP %	System B FP %
Top 1	68.18%	72.72%
Top 3	77.27%	77.27%
Top 5	77.27%	77.27%
Top 10	81.82%	81.82%
Top 20	86.36%	86.36%

The results for the firing pin impression algorithm show that on 68.18% of occasions, system A correlated one out of the two cartridge cases in the top position. System B achieved a percentage of 72.77%. For correlating one out of the two matches within the top twenty both systems achieved a percentage success rate of 86.36%. Figure 5-7 visualises the results in Table 5-15 and clearly shows that both systems performed similarly in terms of overall success rates.

Figure 5-7: Comparison of System A and System B Success Rate for Cartridge Cases (Firing Pin Impression) finding 1 Known Match and Correlation List Length

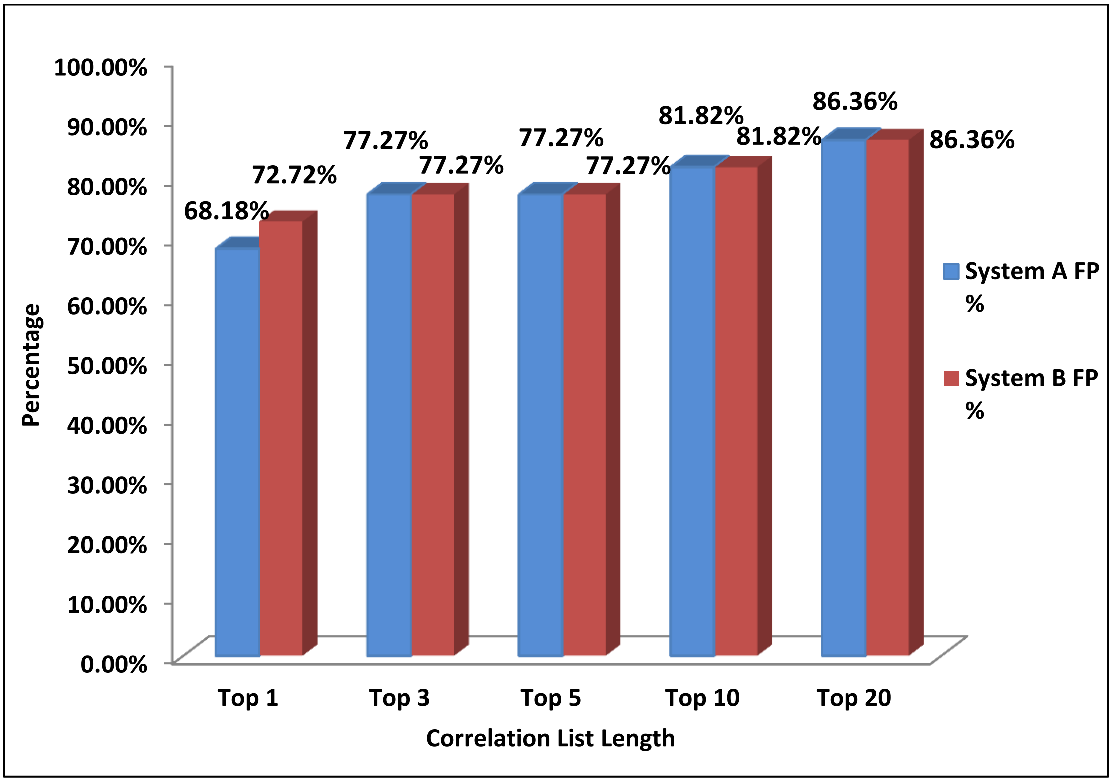
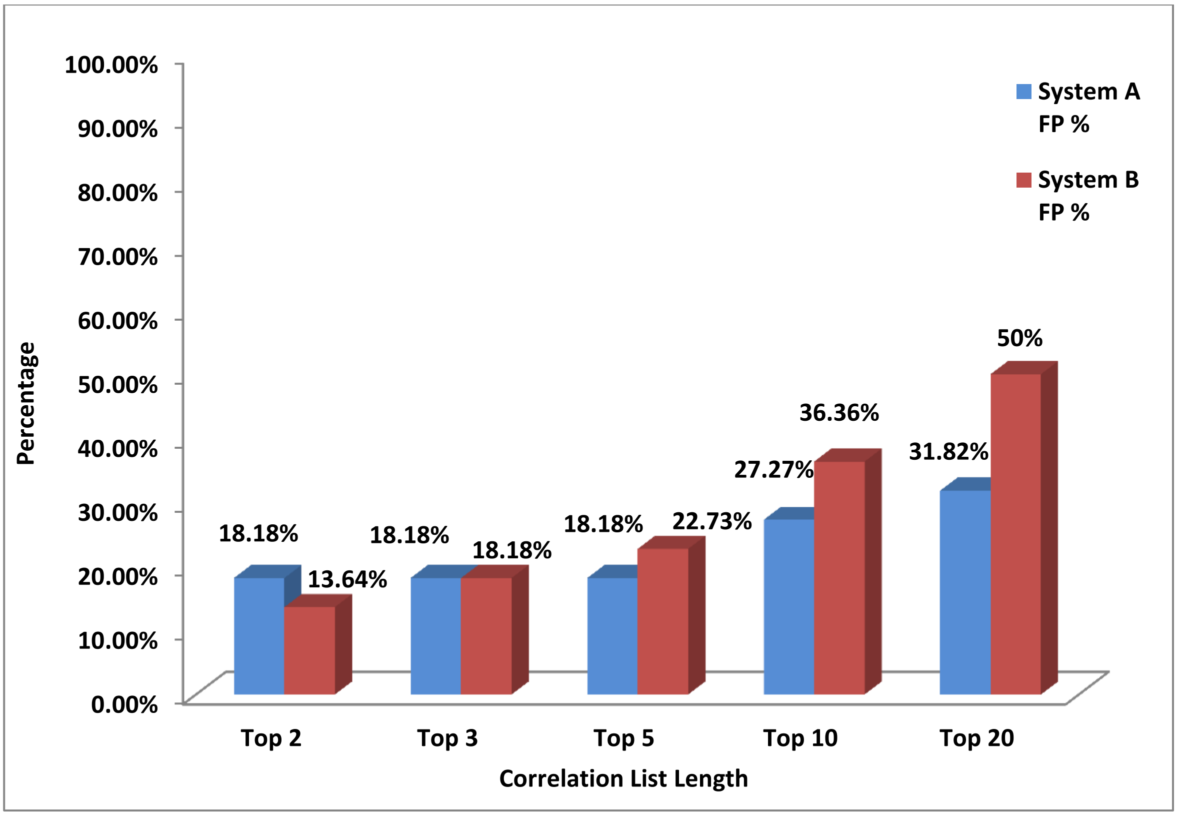


Table 5-16: Success Rate Percentage for Cartridge Cases. System A (Firing Pin Impression) and System B (Firing Pin Impression) finding Both Known Matches and Correlation List Length

Correlation List Length	System A FP %	System B FP %
Top 2	18.18%	13.64%
Top 3	18.18%	18.18%
Top 5	18.18%	22.73%
Top 10	27.27%	36.36%
Top 20	31.82%	50%

Table 5-16 presents the results for each system finding both known matching cartridge cases on correlation lists of varying lengths for the firing pin impression algorithm. System A achieved a perfect result on 18.18% of occasions. System B achieved a perfect result on 13.64% of occasions. For system A, there was no increase in success rate when the correlation list was extended from two cartridge cases to three and five cartridge cases. The increase in success rate only became apparent when the correlation list was extended to ten cartridge cases and twenty cartridge cases. The success rate percentage for system B improved for each different correlation list length. Figure 5-8 illustrates the results in Table 5-16.

Figure 5-8: Comparison of System A and System B Success Rate for Cartridge Cases finding Both Known Matches and Correlation List Length.



5.3.4 Cartridge Cases Accuracy - Comparison with Previous Research

Previous research has been conducted with the IBIS Heritage system. Some of this has been conducted using open case file data (Nennsteil and Rahm, 2006b) whilst other research has focussed on the potential application of the technology to a reference ballistics imaging database (Tulleners, 2001). The research methods utilised previously have been different in many ways. Key differentiating variables include database size, weapon type and the number of test objects. A summary of success rates derived from other research is presented here and in Table 5-17 and Table 5-18. Nennsteil and Rahm (2006b) quote a success rate of between 75% and 95% depending on the circumstances. This refers to the known match being found in the top five positions on the correlation list. Tulleners (2001) examined IBIS Heritage using a background database on 792 cartridge cases and 50 test cartridge cases. The data is presented in such a way that it has been possible to calculate the percentage success rates for correlation lists of different lengths. The percentage success rates for Tulleners (2001) can be seen in Table 5-17 and Table 5-18. George (2004a) examined IBIS Heritage using different combinations of ammunition type. George (2004a) quotes an overall success rate percentage of 48% referring to the known match being correlated in the top ten. It is not specified if this was for the breech face or firing pin algorithm. De Kinder, Tulleners and Thiebaut (2004) correlated 32 test cartridge cases against a database of 600 cartridge cases using IBIS Heritage. They quoted a success rate of 71.8% when finding the match in the top ten positions. The ammunition type of the test cartridge case and the match in the data was the same in the De Kinder, Tulleners and Thiebaut (2004) study. The best ranking was taken from the breech face and firing pin algorithms.

Table 5-17: Research Findings Compared to Previous Research Findings (Breech Face Algorithm)

	Top 1	Top 3	Top 5	Top 10
System A 1 out of 2 BF	72.7%	81.82%	90.91%	90.91%
System A Both KM BF	50%	54.55%	59.09%	63.64%
System B 1 out of 2 BF	54.55%	63.64%	63.64%	77.27%
System B Both KM BF	4.55%	4.55%	4.55%	4.55%
IBIS Heritage BF (Tulleners, 2001)	26%	34%	36%	38%
IBIS Heritage (Nennsteil and Rahm, 2006b)			75%-95%	
IBIS Heritage. (George, 2004a)				48%
IBIS Heritage (De Kinder, Tulleners, Thiebaut, 2004)				78.1%

Table 5-18: Research Findings Compared to Previous Research Findings (Firing Pin Algorithm)

	Top 1	Top 3	Top 5	Top 10
System A 1 out of 2 BF	68.18%	77.27%	77.27%	81.82%
System A Both KM BF	18.18%	18.18%	18.18%	27.27%
System B 1 out of 2 BF	72.72%	77.27%	77.27%	81.82%
System B Both KM BF	13.64%	18.18%	22.73%	36.36%
IBIS Heritage FP (Tulleners, 2001)	26%	30%	32%	42%
IBIS Heritage (Nennsteil and Rahm, 2006b)			75%-95%	
IBIS Heritage. (George, 2004a)				48%
IBIS Heritage (De Kinder, Tulleners, Thiebaut, 2004)				78.1%

5.3.5 Cartridge Cases Accuracy – "Miss" Rate

As described in the previous section on bullet results, the miss rate is used to describe the occasions where one or both matching cartridge cases were correlated outside the top twenty or not at all. The rationale for using this term is that these cartridge cases would be unlikely to be discovered in real case work due to their low position on the correlation list. The accuracy in terms of the miss rate is important because it provides an insight into the percentage of known matches a system could realistically be expected to find.

Table 5-14 shows that for the breech face algorithm, when finding both known matches in the top twenty, system A achieved a success rate of 68.18%. This result reversed shows that on 31.82% of occasions one or both known matches were correlated outside the top twenty. For two of the test cartridge cases (cartridge cases 4A and 19A) both known matches were correlated outside the top twenty. For five of the test cartridge cases (cartridge cases 6A, 8A, 18A, 21A and 22A) one out of the two known matches was correlated outside the top twenty. For system B the success rate percentage for finding both known matches was 4.55% resulting is a miss rate percentage of 95.45% for the breech face algorithm. For fifteen of the test cartridge cases both known matches were correlated outside the top twenty (cartridge cases 4A, 6A, 8A, 9A, 10A, 11A, 12A, 13A, 14A, 15A, 17A, 18A, 20A, 21A and 22A). For 6 of the test cartridges the one of the two known matches was correlated outside the top twenty (cartridge cases 2A, 3A, 5A, 7A, 16A, 19A).

For the firing pin algorithm and correlating both known matches Table 5-16 shows system A achieved a success rate of 31.82% and system 50%. Reversed this shows the miss rates to be 68.18% and 50% respectively for the firing pin algorithm. For system A, for three of the test cartridge cases (cartridge cases 5A, 7A and 19A) both known matches were placed outside the top twenty. For twelve of the test cartridge cases (cartridge cases 1A, 2A, 3A, 8A, 9A, 10A, 11A, 12A, 13A, 14A, 15A and 22A) one out of the two known matches was placed outside the top twenty. For system B, for three of the test cartridge cases (cartridge cases 5A, 19A and 22A) both known matches were placed outside the top twenty. For eight of the test cartridge cases (cartridge cases 1A, 2A, 3A, 8A, 11A, 12A, 14A and 15A) one out of the two known matches was placed outside the top twenty. The calculated miss rates explained here suggest that it is difficult for an examiner to be absolutely sure that there is or is not a match to the questioned cartridge case in the database.

5.3.6 Cartridge Cases Accuracy – False Positives

For the cartridge case breech face algorithm results, the extent to which the systems were capable of producing a perfect result varied dramatically. System B produced a perfect result on just one occasion. System A, however, produced a perfect result on 11 out of 22 occasions. This shows that that for both systems there were non-matching cartridge cases that were presented as being more similar than those cartridge cases that do match. For system A and the breech face algorithm, non-matching cartridge cases were correlated higher than the actual matching cartridge cases on eleven occasions (cartridge cases 4A, 5A, 6A, 7A, 8A, 9A, 11A, 18A, 19A, 21A and 22A. For system B non-matching cartridge cases were correlated higher than the actual matching cartridge cases for every cartridge case with the exception of cartridge case 1A (21 out of 22 test cartridge cases). There were results for both systems where one of the known matching cartridge cases was correlated in the top position whilst the other matching cartridge case was correlated in a much lower position resulting in a large number of non-matching cartridge cases being presented as more similar than the second matching cartridge case.

Consider the result system A produced for cartridge case 21A. Cartridge case 21C has been correlated at position 1 whilst cartridge case 21B has been correlated at position 168 meaning that 166 non-matching cartridge cases have been ranked as more similar than the second actual matching cartridge case. A similar result is observed for system B for cartridge case 20A where cartridge case 20B has been correlated at position 1 and cartridge case 20C has been correlated at position 235 meaning that 233 non-matching cartridge cases have been ranked in a higher position than the second actual matching cartridge case. It is unlikely that these cartridge cases would be discovered in a real life situation as examiners generally only examine the top twenty suggested matches. This raises the possibility of links between crimes remaining undiscovered. The other implication of this type of result is that the presence of non-matching cartridge cases in high correlation list positions may mislead the examiner into declaring a false positive match. An example of this type of result is that generated by both systems for test cartridge case 18A. System A has correlated cartridge case 18B at position 5 and system B has correlated cartridge case 18B at position 2. This shows that there are a small number of cartridge cases that would be examined and the issue would be the extent to which the presence of the non-matching cartridge cases would affect the conclusions of an examiner. This is especially true of situations where there is a high degree of similarity between the cartridge cases in the top twenty. The effect of ballistics analysis systems on firearms examiners is discussed in a later section of this Chapter.

For the firing pin algorithm, system A correlated non-matching cartridge cases higher than the actual matches on 18 occasions (cartridge cases 1A, 2A, 3A, 4A, 5A, 6A, 7A, 8A, 9A, 10A, 11A, 12A, 13A, 14A, 15A, 19A, 21A and 22A) . System B correlated non-matching cartridge cases higher than the actual matches on 19 occasions (cartridge cases 1A, 2A, 3A, 4A, 5A, 7A, 8A, 9A, 10A, 11A, 12A, 13A, 14A, 15A, 17A, 18A, 19A, 21A and 22A). There are examples where a large number of non-matching cartridge cases have been correlated above the known matching cartridge cases. For cartridge case 12A, system A has placed 313 non matching cartridge cases above the second known matching cartridge case and system B as placed 343 non matching cartridge cases above the known match. As was previously discussed for the breech face results, it is unlikely that this cartridge case would be discovered in a real life situation as examiners generally only examine the top twenty suggested matches. Again, this raises the possibility of links between crimes being undiscovered despite the evidence being present. The results are also similar to the breech face algorithm results because the presence of non-matching cartridge cases in high correlation list positions may mislead the examiner into declaring a false positive match. An example of this type of result is that generated for cartridge case 21A. Both systems have correlated both cartridge cases within the top twenty. System A has placed the known matching cartridge cases at position 7 and 11 and system B has placed the known matching cartridge cases at positions 2 and 6. This shows that there are a small number of cartridge cases that would be examined and the issue would be the extent to which the presence of the non-matching cartridge cases would affect the conclusions of an examiner. This is especially true of situations where there is a high degree of similarity between the cartridge cases in the top twenty. These results are used to define error rates for the systems and are discussed later in this Chapter.

As previously noted through the analysis of the bullet results in an earlier section of this Chapter, the performance of ballistics analysis systems, especially with regards to accuracy can affect a police investigation it terms of time it takes to return evidence or intelligence to the investigating officer. Results where non-matching cartridge cases have been presented in a higher correlation list position than known matching cartridge cases are important in this context because they make the task of the examiner more complex and at worst may lead an examiner to reach a false conclusion. The presence of non-matching cartridge cases in positions above the actual match may also increase the time it takes for an examiner to find the actual match, effectively creating “noise” in the results. These factors could potentially waste investigation time and create confusion in the investigation.

5.3.7 Cartridge Cases Accuracy – Total Length of Correlation List and False Positives

Where the result for a test cartridge case is not a perfect match then by definition, there has been a non-matching cartridge case or cases presented as being more similar than the actual known matching cartridge case or cases. Recall that for the bullet results, the total correlation list length varied for each test bullet. This is not the case for the cartridge case results. Each cartridge case in the database has a correlation list containing every other cartridge case in the database. The length of each cartridge case correlation list is therefore 389 cartridge cases. However, the same point can still be made regarding the number of known non-matching cartridge cases that are placed in higher positions on the correlation list than the actual matching cartridge cases. Table 5-19 shows the number of non-matching cartridge cases ranked in a higher position than the actual matching cartridge cases for each of the test cartridge cases for both the breech face algorithm and the firing pin algorithm. This is referred to as the number of false positives.

Table 5-19: Number of False Positives for System A and System B (Cartridge Case Breech Face Algorithm and Cartridge Case Firing Pin Impression)

	Test Index	System A BF Number of False Positives	System B BF Number of False Positives	System A FP Number of False Positives	System B FP Number of False Positives
1	**1A**	0	0	181	190
2	**2A**	0	42	55	164
3	**3A**	0	200	174	58
4	**4A**	43	361	7	2
5	**5A**	8	215	107	255
6	**6A**	93	45	4	0
7	**7A**	11	266	33	16
8	**8A**	29	218	72	46
9	**9A**	2	355	178	1
10	**10A**	0	112	47	11
11	**11A**	1	82	319	333
12	**12A**	0	79	313	343
13	**13A**	0	195	219	6
14	**14A**	0	40	285	357
15	**15A**	0	76	197	148
16	**16A**	0	221	0	0
17	**17A**	0	139	0	8
18	**18A**	137	232	0	9
19	**19A**	179	275	65	64
20	**20A**	0	233	0	0
21	**21A**	166	31	9	4
22	**22A**	155	26	80	174

5.3.8 Cartridge Cases Accuracy - Overall Accuracy of the Systems

The results of the experimental research with cartridge cases have revealed that the systems are working differently and are producing different results. This is to be expected as it is assumed that both manufacturers are using different data acquisition and correlation techniques. For the breech face algorithm, an identical result was produced on just one occasion (cartridge case 1A). Therefore on 21 occasions a different result was produced. For the firing pin algorithm, an identical result was observed on two occasions (cartridge cases 16A and 20A). A similar result was observed on a further six occasions (cartridge cases 1A, 3A, 11A, 12A, 14A and 15A). Therefore on 20 occasions a different result was observed. This demonstrates the fact that the systems are working differently and produce different results.

The results for both cartridge case algorithms also show that neither system is completely accurate (as was described in the previous section on bullet results, neither manufacturer make a claim of total accuracy). Each cartridge case had two known matches in the database and the result indicate that for both systems and both algorithms the performance is better when correlating one out of the two known matches as opposed to both known matches. The success rate percentages for finding one out of the two matches for the breech face impression were 72.7% for system A and 54.55% for system B. When finding both known matches, the success rate percentages dropped to 50% and 4.55% respectively. For the firing pin impression, the success rate percentages for finding one of the two matches was 68.18% (system A) and 72.72% (system B). When finding both known matches, this dropped to 18.18% and 13.64% respectively. These results clearly show that there are multiple occasions where non-matching objects are correlated in higher positions than the actual matching objects.

For the cartridge case breech face impression, a perfect result was achieved on 50% (system A) and 4.55% (system B) of occasions showing that on 50% of occasions and 95.45% of occasions respectively, non-matching cartridge cases were presented to the user in higher positions than actual matches. For the firing pin impression, a perfect result was achieved on 18.18% (system A) and 13.74% of occasions (system B) resulting in non-matching cartridge cases being correlated higher than actual matches on 81.82% and 86.26% of occasions respectively. Although there were not any occasions where a cartridge case was not correlated at all, there are multiple occasions where a matching object has been correlated outside the top twenty and many of these cartridge cases were correlated at considerably low positions. It is likely that these cartridge cases would not be discovered in a real-life situation. The accuracy of the systems in terms of error rates is discussed in a later section of this Chapter.

5.3.9 Cartridge Cases – Correlation List Length

The impact of ballistics analysis systems on police investigations was discussed in the bullet results section with specific relevance to the correlation list length and the number of bullets or cartridge cases that a ballistics expert should examine. It was described how there are no standards in place to determine what length the correlation list should be although previous research has suggested varying correlation list lengths of ten objects (IBIS training manual), five objects (Silverwater and Koffman, 2000) between five and ten objects (Nennsteil and Rahm, 2006a) and twenty objects (Brinck, 2008). When correlating cartridge cases, each system has two different algorithms, one examining the breech face impression and the other examining the firing pin impression. Each system therefore produces two different correlation lists, meaning that if the examiner was to examine the top twenty objects on each list, they would potentially be examining forty objects. It could of course be less than this if the same object appeared on both correlation lists. But the implication of this is that any findings that highlight the ideal correlation list length could be of importance in reducing examiner workload particularly for cartridge cases due to the two different algorithms.

As previously described, the research conducted for this Thesis differed slightly to previous research as there were two matching objects in the database for each test object meaning that there are two success rate scores, one for finding one out of the two known matches and one for finding both known matches. These success rates can contribute to the debate on what the correlation list length should be. As it is of vital importance to find all the potential links in a database, the success rates for correlating both known matches have been used to inform the ideal correlation list length. When finding both known matches for the breech face impression algorithm, the results for system A suggest that the correlation list should be examined up until position twenty as the success rate increased as correlation list increased. For system B, a perfect result was obtained on 4.55% of occasions. This percentage did not improve by extending the correlation list length to twenty objects

For the firing pin algorithm, for finding both known matches, both systems success rate increased as the correlation list increased to contain twenty objects. . Table 5-20 shows the suggested correlation list lengths for the cartridge case breech face algorithm and the firing pin algorithm for both systems.

Table 5-20: Suggested Correlation List Lengths for the Cartridge Case Breech Face Algorithm and Firing Pin Algorithm

	System A	System B
CC BF Both Known Matches	20	2
CCFP Both Known Matches	20	20

5.3.10 Cartridge Cases – Effect of Ammunition Type

The ways in which ballistics analysis systems are used should be in such a way as to ensure the best possible performance. This should in turn ensure that a system and the correlation algorithms are as accurate as possible. The results have demonstrated occasions where one bullet or cartridge case was correlated at position one and the second matching bullet or cartridge case has been correlated at a lower position on the list. Non-matching bullets or cartridge cases have been placed in between. It is therefore suggested that ammunition type and the resultant quality of the marks on the ammunition may have been a variable that contributed to this result. Understanding the extent to which this is true could lead to recommendations for laboratories using these systems. For example, if it is the case that the systems are more successful when correlating ammunition of the same type then procedures could be put in place to ensure that multiple samples are uploaded to a system for each type of ammunition already present in the database. This approach has been suggested by Nennsteil and Rahm (2006a) and Argaman, Shoshani and Hocherman (2001).

The ammunition that was used for the experimental research in this Thesis was generated by multiple individuals and laboratories across Europe. It was decided in the early stages of the methodology design that it would be impractical to try and use the same one or two brands of ammunition because there was no guarantee that every laboratory would have the same ammunition type readily available. The priority at that time was generating a sample that was of sufficient size to enable the results to be valid. It also should be noted that the overall aim of the experimental research at that time was enabling each system to capture the same physical ammunition samples to enable the results to be discussed within the same terms of reference. The key point was the same bullets and cartridge cases being acquired by each system to observe similarities and differences in the data rather than the design of a performance test. However, one of the key findings of the research has been that there is a difference in success rate when finding one out of the two known matches and both known matches. With the cartridge case sample, it has been possible to examine the ammunition type and discuss the results knowing the brand of ammunition. Table 5-21 shows which objects are of the same ammunition type for each test object and the correlation list positions for each system for both algorithms.

Table 5-21: Cartridge Case Result Matrix for System A and System B and Ammunition Type (Breech Face Algorithm and Firing Pin Algorithm)

Test CC	KM 1 CC	Sys A BF	Sys B BF	Sys A FP	Sys B FP	KM 2 CC	Sys A BF	Sys B BF	Sys A FP	Sys B FP
1A	1B	1	1	1	1	1C	2	2	183	192
2A	2B	1	1	3	1	2C	2	44	57	166
3A	3B	1	1	1	1	3C	2	202	176	60
4A	4B	34	363	9	4	4C	45	33	1	1
5A	5B	1	13	98	257	5C	10	217	109	212
6A	6B	1	47	1	1	6C	95	1	6	2
7A	7B	2	268	35	14	7C	13	109	23	18
8A	8B	5	220	74	1	8C	31	8	3	48
9A	9B	1	7	180	3	9C	4	357	1	1
10A	10B	2	114	49	13	10C	1	1	1	1
11A	11B	3	1	1	1	11C	2	84	321	335
12A	12B	1	1	1	1	12C	2	81	315	345
13A	13B	1	1	1	1	13C	2	197	221	8
14A	14B	1	9	1	1	14C	2	42	287	359
15A	15B	1	1	1	1	15C	2	78	199	150
16A	16B	2	163	1	1	16C	1	223	2	2
17A	17B	2	2	2	1	17C	1	141	1	10
18A	18B	5	2	1	8	18C	139	234	2	11
19A	19B	116	75	67	63	19C	181	277	41	66
20A	20B	1	1	1	1	20C	2	235	2	2
21A	21B	168	1	7	2	21C	1	33	11	6
22A	22B	157	1	12	32	22C	1	28	82	176

Table 5-21 Key: Green denotes cartridge cases that are of the same ammunition type.

Research conducted by Nennsteil and Rahm (2006a) suggested that test fires that are to be inputted to an automated system should be of the same brand of ammunition as the evidential object seized at the crime scene. This finding was also presented by De Kinder, Tulleners and Thiebaut (2004). The research conducted for this Thesis also provides some evidence to support the theory that automated systems are more successful when correlating cartridge cases that are of the same ammunition type. It is probable that ammunition of different types is made from variations of metal alloys and hence the materials will have different hardness values. As a consequence of these different hardness values, the marks imprinted on the ammunition be it bullets or cartridge cases will be less apparent on harder materials. This could go some way to explain why differing ammunition types appear harder to correlate.

Table 5-21 shows that for 13 out of the 22 test cartridge cases, there was one out of the two cartridge cases in the database that was of the same ammunition type. These are highlighted in green in the table above. The ammunition type of the test cartridge case and the ammunition type of the two matching cartridge cases enables the effect of ammunition type to be considered. A measurement of the occasions where the cartridge case of the same ammunition type as the test cartridge case was correlated above the other object of a different ammunition type has been conducted. The results are presented in Table 5-22.

Table 5-22: Occasions where the Same Ammunition Type as Test Cartridge Case was Correlated Higher than the Other Cartridge Case

	System A BF	System B BF	System A FP	System B FP
Occasions where same ammunition type as test cartridge case was correlated above other cartridge cases	9	13	11	13
Percentage	69.23%	100%	84.62%	100%

The results whilst somewhat limited due to the small sample size of thirteen cartridge cases show that system B correlated the cartridge case of same ammunition type above the other cartridge case on 100% of occasions for both algorithms. The results for system A are similar showing that the cartridge case of the same ammunition type was correlated above the other cartridge case on 9 out of 13 occasions (69.23%) for the breech face algorithm and 11 out of 13 occasions for the firing pin algorithm (84.62%). These results clearly demonstrate that ammunition type is an important variable that affects the performance of automated systems and provides evidence to support the findings of Nennsteil and Rahm (2006a) and De Kinder, Tulleners and Thiebaut (2004). It may be suggested that when test fires are acquired by a system, there should be multiple samples acquired, one of each ammunition type that is already in the database. Argaman, Shoshani and Hocherman (2001) also made this suggestion. There is a problem however, that arises because Nennsteil and Rahm (2006a) suggested that the success rate decreases as database size increases and acquiring multiple samples will lead to a greater database size. It is likely that there is a compromise to be made between the overall database size and the policy with regards to the type of ammunition and number of samples uploaded. However, the nature and characteristics of this compromise is an area for further research.

5.3.11 Comparison of the Breech Face Results and the Firing Pin Results

The comparison of the breech face results and the firing pin results is important because having two sets of results to examine for the same cartridge case potentially doubles the time taken for an examiner to reach a conclusion. It is for this reason that the two sets of results are compared and discussed because any findings that can reduce the time taken for an examiner to reach a conclusion are important. Table 5-21 shows the correlation list positions for cartridge cases for systems A and B and for both the breech face algorithm and the firing pin algorithm. The analysis of the results presented thus far has treated the algorithms as separate entities – the results for the breech face algorithm of each system were analysed separately to the firing pin impression results. This was done to ensure that any conclusions were drawn as a results of comparing like with like. A user of these systems would of course be able to switch between the firing pin results and the breech face results depending on the specific situation and the type of classmarks they were examining.

However, comparing the breech face results with the firing pin results for each system, as presented in the above table can yield some important points for discussion. Table 5-21 demonstrates the variance in the results. There was not a single occasion where there was agreement between both algorithms for both systems. Furthermore, there was wide variance within systems. Consider the comparison of the breech face algorithm results and firing pin impression results for system A. There are only two occasions when there is complete agreement for the two algorithms (cartridge cases 17A and 20A). For system B there are no occasions when the same result is observed for the breech face algorithm and for the firing pin algorithm. This may be expected as the breech face impression may be of better quality than the firing pin impression and vice versa, resulting in a situation where the results vary. Consider the results for cartridge case 1A. Both systems have correlated cartridge case 1B in the top position for both the breech face algorithm and the firing pin algorithm perhaps suggesting that this cartridge case has excellent quality marks for both the breech face and the firing pin. Both systems have also correlated cartridge case 1C in position 2 for the breech face algorithm but have correlated the same cartridge case at a much lower position for the firing pin impression (system A position 183 and system B position 192). This suggests that the breech face impression for cartridge case 1C is of good quality whilst the firing pin impression may not be.

There are also occasions where the comparison of results between systems and algorithms suggest differences between the ways in which the systems are operating regardless of the quality of the marks on the ammunition. Consider the result obtained for cartridge case 20A. Both systems have achieved the same perfect result for the firing pin algorithm. The breech face algorithm has however produced a different result. System A has achieved a perfect result whilst system B has correlated one known match at position one and the other at position 235. This suggests that there has been an interaction specific to system B between the marks on the ammunition and the correlation algorithm employed.

5.3.12 Effect of the Operator on Both Bullet and Cartridge Case Results

It is recognised that the different operators of each systems could have contributed to the variance between the systems observed in the results. However, whilst recognising this factor there were multiple steps taken to reduce the effect of the operator and control this variable.

As described in Chapter four, both manufacturers that participated were asked to provide an operator to enter the bullets and cartridge cases onto the database. The rationale behind this decision was that there was no suitably qualified person who could operate both systems to a sufficiently high standard. By asking the manufacturers to provide an operator, the rationale was that it was in the interests of each manufacturer to provide a suitably qualified person. The expertise of the operator of each system is not limited to just ballistics expertise. As each operator had information on the proprietary methods employed to capture and correlate images, there was an additional level of expertise relating to the interaction between the images and the proprietary correlation methods. This information was unknown to the author but resulted in a situation where the operator of each system was not only qualified to identify distinguishing features from a ballistics standpoint but also qualified to understand the strengths and weaknesses of the particular system ensuring that the data captured was of a high quality.

It should also be noted that some parts of the process are automated to a greater extent than others. This is demonstrated by the fact that less user interaction is required when marking key features on cartridge cases than when marking striations on bullets. Often the only user input for cartridge cases is marking the outer edge, the breech face impression and the firing pin impression. These features are more easily identifiable than bullet striations. There was more variance in the results between systems for the cartridge case condition suggesting that the effect of the operator did not play a significant role. For the cartridge case breech face impression algorithm the systems produced the same result on one occasion and for the firing pin impression the same result was observed on two occasions. This contrasts greatly with the bullet condition where the same result was observed for both systems on eight occasions despite the fact that there is more opportunity for different inputs by different operators.

It should also be noted that the results of the experimental work has been communicated and discussed with each manufacturer in some detail and neither has raised any concerns relating to the quality of the data capture or the correlation results.

The next section considers the results and defines error rates for the systems examined. The success rates presented in this section are explored in greater detail and used to calculate and define error rates.

5.4 - Definition of an Error Rate for Automated Systems

Consider the results described in this Chapter in a different light and outside of the debate on subjectivity in forensic ballistics. If an objective standpoint is taken and the results are considered to be either correct (a perfect result) of incorrect (every other occasion where a perfect result was not achieved) then an error rate can be defined, calculated and presented. This is a perfectly reasonable approach to take as this experiment was controlled in order for the matches and non matches to be known. The known matches and non-matches are documented and an audit trail is in place so that every bullet and cartridge case can be traced back to the source firearm. Therefore, it is extremely unlikely that there have been errors in the indexing process. Consequently the terminology relating to “correct” and “incorrect” results can be used with an extremely high confidence level.

5.4.1 Total Error Rate Percentage

It should be noted that for some of the test objects (bullet or cartridge case), one object will have been correlated in position one and the other will have been correlated in a position other than two. This is still considered to be an incorrect result as non-matching objects were presented to the user higher than the second actual matching object. There was also a single occasion for bullet 10A where no correlation list was produced. This is also considered as an incorrect result as the matching bullets were in the database but not successfully correlated. The error rate in this context is defined by the author as follows:

> *The occasions where the system has produced a result that is incorrect; a perfect result has not been achieved and whilst one of the two objects may have been correlated in the top position, a non-matching object or objects is presented in a higher position than the second actual matching object. Alternatively, no correlation list was produced despite matches being present in the database.*

This will be called the **<u>Total Error Rate Percentage</u>**. Table 5-23 shows the Total Error Rate percentages for each system and each experimental condition.

Table 5-23: Total Error Rate Percentage for System A and System and Every Condition

	System A Error Rate	System B Error Rate
Bullets	34.78%	56.52%
Cartridge Cases (BF)	50%	95.45%
Cartridge Cases (FP)	81.82%	86.36%

5.4.2 False Positive Error Rate

The results also clearly show that there are occasions where a non-matching object has been correlated in the top position. This is by definition a false positive result. Consider an alternative definition of the error rate – in this case, the definition is:

> *Any occasion where a non-matching object has been correlated in the top position above the known matching objects.*

This will be called the **False Positive Error Rate**. Table 5-24 shows the error rate for this condition.

Table 5-24: False Positive Error Rate for System A and System B and Every Condition

	System A Error Rate	System B Error Rate
Bullets[17]	17.39%	39.13%
Cartridge Cases (BF)	27.27%	45.45%
Cartridge Cases (FP)	31.82%	27.27%

Table 5-23 and Table 5-24 show that whichever definition of error rate is applied, the error rates are high and clearly demonstrate that innovation and improvement is needed to reduce the error rates. Despite the complexity and variance in the results that has been demonstrated, the performance of the systems can be defined in terms of the error rates. The effect of any improvements or adjustments to each system can be assessed by the impact on the error rates as defined by the author in this Thesis. It may also be useful to apply these definitions of error rates to any future research. It would certainly be useful to consider the success rates and error rates of a system together, as both calculations present different dimensions of the capabilities of automated systems.

The next section discusses the conclusions of the research conducted and aims to place the findings if the research in the context of research discussed in the literature review.

[17] There was a single occasion for bullets where a correlation list was not produced. This was for bullet 10A. Therefore as there was no correlation list produced there were also no false positives produced.

Chapter 6 – Conclusions

6.1 – Results and Conclusions in the Wider Context of Policing Issues

The literature review identified the fact that there is a lack of multidisciplinary research combining research in the forensic ballistics arena with research conducted on gun crime. One of the aims identified in Chapter three was to address this by placing the results of the experimental research conducted in this Thesis back into the context of policing issues relevant to gun crime. This section discusses the results in the context of some of the issues raised in the literature review and aims to draw conclusions.

6.1.1 Use of Systems and the Rate of Gun Crimes

Home Office statistics showed that in 2008/09, gun crime accounted for 0.3% of all offences in the UK representing over 14,000 crimes (Smith et al, 2010). This figure includes air weapons. Excluding air weapons, the number of gun crimes was 8,208. It is probable that there is not ballistics evidence in the form of bullets, cartridge cases or firearms recovered from every crime because there will have been occasions where the firearm was used as a blunt weapon or to threaten a person. It is also possible that is some of these cases, the firearm may have been an imitation weapon. The number of offences officially recorded does, however, provide an insight firstly into the scale of the problem facing the police but also secondly the resultant workload of forensic ballistics examiners in the UK This is despite the fact that compared to other countries, crimes involving firearms occur less frequently in the UK than in other countries (Krug et al, 1998) - arguably because of the nature of the law, in the UK governing firearm possession (Warlow, 1997; Spritzer, 1998). However, consider if there was a single bullet or cartridge case recovered from just half of the crimes involving firearms reported each year and the workload this would generate for ballistics experts. Also consider the time it would take for these exhibits to be uploaded to a ballistics analysis system, the correlation lists to be examined and then the actual bullets or cartridge cases to be examined and a report produced. Many ballistics laboratories examine the top twenty bullets or cartridge cases on a correlation list in order to have a good chance of finding the match. However, this workload put in the context of the number of crimes that are occurring each year clearly suggests that innovation is needed to reduce the workload of ballistics examiners. One of the contributions of this Thesis has been to suggest ideal correlation list lengths based on the sample of ammunition examined. For system A correlating bullets, it was suggested that the top twenty matches should be examined and for system B it was suggested that the top ten matches should be examined as there was no improvement noticed by extending the list to twenty objects. For the cartridge case firing pin algorithm, the results suggest that the top twenty objects should be examined for both systems. For the breech face algorithm, the top twenty should be examined for system A. For system B, no improvement was noticed beyond a list of two objects.

The points to make here are twofold; firstly that given a certain sample of ammunition, an ideal correlation list length can be calculated based on the use of a system in a particular context. The results for this Thesis support examining the top twenty for cartridge cases and bullets. However, as only one firearm type was used and the database contained 390 items, this recommendation should not be interpreted absolutely but more as a guideline. The results do show that by carefully examining data that is already being collected, recommendations can be made as to the best way to use technology with the specific focus on saving time and improving efficiency. It may be the case that laboratories routinely examine the top twenty objects but that also there has not been a calculation of the effectiveness of this policy for that particular laboratory. It could be the case that a high proportion of matches are found in the top ten in a particular laboratory under their specific conditions. The results of this Thesis have shown that measuring performance using existing data can contribute to clearly defined recommendations regarding correlation list length. This is important given the fact that investigations involving the use of firearms can be complex as the types of crime are varied (Hales, Lewis and Silverstone, 2006). There are also difficulties such as reluctance of victims and witnesses to cooperation with the police (Hales et al, 2006; Squires, 2008). There is also the added complexity in some cases of gang involvement (Vaughan et al, 1996; Bullock and Tilley, 2002; Decker and Curry, 2002; Marshall, Webb and Tilley, 2005; Hales et al, 2006; Hayden et al, 2008 and Hallsworth and Silverstone, 2009). These factors clearly imply that as gun crime investigations can be inherently difficult, any improvements to the process such as reducing the time taken to return evidence or intelligence to the investigating officer can be extremely valuable.

The number of bullets or cartridge cases on a correlation list that an expert has to examine is directly linked to the accuracy of a system. The more accurate a system, the smaller the number of objects on the correlation list that need to be examined. Nennsteil and Rahm (2006a: 21) point out that an ideal correlator, "would have each positive match at position one of the hit list". The results of this Thesis provide evidence to show that both system A and system B are not accurate enough to correlate all the known matches in the top position on all occasions. However, some of the results indicate that both system A and system B are more accurate in some conditions than others. Take the cartridge case firing pin algorithm results as an example. The top twenty correlation list positions were considered and both systems found one of the two known matches on 86.36% of occasions. Further work improving accuracy could aim to reduce the correlation list size (finding 86.36% of known matches on a correlation list containing five objects for example) or alternatively improving the percentage success rates (finding 100% of the known matches on a correlation list of twenty objects for example). The important finding is that the inaccuracy of the systems on some occasions is directly related to the increased workload of ballistics examiners. Innovation and optimisation of the technology could reduce this workload and improve the speed at which evidence can be returned to the investigating officer. Such improvements would not only improve the efficiency of ballistics examinations but also improve confidence in the forensic ballistics – especially important given the challenges that have been made to the discipline (Schwarz, 2004; Schwarz 2007; Edwards, Gatsonis and Kafadar, 2009.) The findings of this research so suggest that approaches based on alternative technologies are required rather than optimising current technology. One such example has been proposed by Xie et al (2009). It is possible that techniques such as this, may result is a greater amount of detail being able to be captured about a surface. In turn this increased detail may lead to more precise measurements and correlations. The statistics presented by Smith et al (2010) whilst confined to England and Wales suggest that there are a vast number of gun crimes that yield forensic evidence for evaluation. The benefits to police officers of more accurate technology would mainly concern the speed of having evidence returned that may generate investigatory leads. This is especially important given the difficulties of investigating crimes involving firearms. (Hales et al, 2006; Squires, 2008)

6.1.2 Alternative Research Methods to Quantify Gun Crime

Squires (2008) identified the fact that there is a gap in intelligence created by crimes that are not reported to police in the UK. As well as creating an intelligence gap, unreported crimes result in a situation where it is difficult to fully quantify the number of crimes involving firearms that do occur. Consider the 8,208 crimes reported in 2008/09 (Smith et al, 2010). It is unknown the extent to which this figure is an accurate reflection of reality. Research has been conducted using other data to try and address this problem. Examples are those studies conducted by Pershad et al (2005), Lepik and Poldsam (2007), Verzeletti et al (2009) and Karlsson et al (1993). All examined medical data concerning gunshot wound related hospital admissions to try and ascertain the true rate of gun crime. Holloway and Bennett (2004) also utilised different research methods by interviewing offenders to try and quantify crimes involving firearms.

By their very nature ballistics analysis systems collect a wide range of data and this has been demonstrated by the research in this Thesis and also by the use of a different system in the UK (NABIS, 2011). Some of this data are specific to the bullets and cartridge cases such as ammunition type, calibre and inferred firearm type. There is also ancillary data recorded by these systems such as case reference numbers and temporal information relating to the time and date of offences. One potential area for exploration could be the consideration of data stored in ballistics analysis systems when collating official statistics. For example, a simple count of the number of exhibits and cases on a national database could be compared to the national count of crimes involving firearms reported to the police. Intuitively it would be expected that the number would be similar but because it is unknown the extent to which this happens, the numbers cannot be compared. Further research could be conducted using the data collected by these systems such as the ammunition type and calibre of recovered ballistics exhibits. This does happen in the UK (NABIS, 2011) but it is not known the extent to which this data is considered when compiling official statistics. Furthermore, it is not known the extent to which this happens outside the UK. Such research would be complementary to official statistics, would provide a different dimension to the official statistics and would arguably help address the intelligence gap created by unreported crimes identified by Squires (2008).

6.1.3 Variance in Gun Crime between Countries and Different Solutions to the Problem

The literature review demonstrated that the nature and characteristics of gun crime varies significantly between countries and sometimes within countries. Krug el al (1998) examined firearms deaths across thirty six countries and found that the USA had a much higher incidence of firearms deaths than Europe. Krug el al (1998) also found that firearms deaths tended to be fewer in number in the Asian nations of Japan, South Korea, Hong Kong, Singapore and Taiwan. The main point that Krug el al (1998) demonstrated is one of variance in gun crime rates between countries. Further research such as that conducted by Agozino et al (2009) shows that different countries face different problems relating to gun crime. Agozino et al (2009) examined firearms crimes in the West Indies and demonstrated a rise in firearms crimes over six years and also showed that firearms murders were less likely to be solved than other murders. This was attributed to the availability of small arms and also to retaliation murders. Contrast the situation in the West Indies with the situation in Canada as described by Sheptycki (2009) who reported the magnified perceived threat of gun crime despite evidence to the contrary showing a fall in gun crime. A further differentiating factor concerning the nature of firearms crimes was described by Campbell (2010) who found that the percentage of homicides committed using firearms was twice to five times higher in Ireland than in England and Wales. The point made by Krug el al (1998), Agozino et al (2009), Sheptycki (2009) and Campbell (2010) is that there is good evidence to show that the nature and characteristics of gun crime varies between countries. It is therefore logical to suggest that the solution to the problem and also the techniques, tools, and equipment needed to tackle the problem will also differ between countries. One area of differentiation may be the forensic equipment utilised to examine ballistics evidence.

The USA has a high rate of crimes involving firearms. It is fair to suggest that there will be a correspondingly high number of ballistics exhibits submitted to laboratories for examination and that these exhibits will be required to be uploaded to ballistics analysis systems. In this case, it is likely that the main capability an installed system will need to have, will be speed of acquiring the bullets or cartridge cases. Accuracy will also be a concern due to the likely large size of the database. Contrast this with a country that has a smaller problem. It is likely that the number of ballistics exhibits is smaller and also that these countries are maintaining smaller databases. Whilst accuracy is still important, the speed at which the objects are acquired may not be of such importance if there is no backlog of cases. These different requirements relating to ballistics analysis systems are a critical point but are often overlooked. Research conducted in a controlled manner such as that conducted for this Thesis, can inform the purchasing decisions that police forces and forensic laboratories make regarding automated systems.

Nutley, Davies and Tilley (2000) describe some specific interventions that can be applied to the evidence based procurement of ballistics analysis systems. Firstly, research findings should be communicated simply and clearly. This is important as procurement decisions may lie with non-experts. Nutley, Davies and Tilley (2000) also suggest that the effectiveness of the implementation should be monitored. It is interesting to note that the implementation of evidence based approaches faces many of the same barriers as adoption of new innovative technology. Moore (1999) described some of the problems relating to successful technology adoption. Some of the strategies that enable successful adoption such as training, the use of product champions and introducing targets to ensure use of the product are very similar to interventions recommended by Nutley, Davies and Tilley (2000) to ensure the use of evidence based approaches by police practitioners.

There are however, two barriers to this approach created by the current situation with regards to ballistics analysis systems. The first is that the differences in functionality of different systems are not systematically known or documented preventing procurement decisions such as the ones described above being made. This is probably because of the difficulties of carrying out such research. These difficulties were documented in Chapter four and included considerations such as the time and cost of such research. The results of this Thesis have demonstrated that it is possible and achievable to document these differences between systems by conducting a controlled experiment using the same ammunition set. The results not only show that conducting research such as this is possible but also that the results yielded are valuable. It is also suggests that more research of this type should be undertaken prior to the procurement and installation of any new system.

The second barrier is the lack of interoperability between systems meaning that procurement decisions are often taken on the basis of an entire country or region to ensure that data can be shared. This Thesis has demonstrated that interoperability between systems is unlikely to be realised without the cooperation of the manufacturers due to the disagreement between the systems demonstrated in the results (see bullets 2A, 3A, 4A, 13A, 14A and 21A as examples).

The lack of documented differences between systems and lack of interoperability between systems unfortunately suggests that evidence based procurement is not currently happening. This is despite the fact that such an approach could improve the investigation and detection of gun crime offences by enabling police forces to use the equipment that is best suited to their specific circumstances.

6.1.4 Effect of Legislation

Research for this Thesis analysed the capabilities of two systems to correlate the same sample of bullets and cartridge cases. This has enabled issues such as interoperability between systems to be considered with an evidence base. There are other functionalities of these systems which may yield useful data aside from the primary function of cross-correlating bullets and cartridge cases. Furthermore, there are many applications for this but one example could be measuring the effect of legislative changes. Research to date has focussed on the effect of legislation on gun related deaths (Ozanne-Smith et al, 2004; Niederkrotenthaler et al, 2009). There is perhaps a need to consider the impact that legislation has on the forensic detail of the firearms consequently being used in crimes. The work conducted has shown that ballistics analysis systems routinely capture forensic ballistics data such as calibre, ammunition type and inferred firearm type because this information is required by the correlation algorithms. A suggested way to measure the specific impact of legislative changes could be through the collection, harvesting and analysis of data stored on ballistics analysis systems. Warlow (2007) explained how reactivated firearms became problematic in Britain following the introduction of legislation banning handguns. This type of trend would have an impact on the forensic examinations being carried out and would be captured in the data stored on ballistics analysis systems. It is possible that in some cases ballistics analysis systems are storing data that has untapped intelligence potential regarding trends in firearm use.

The benefits of applying this approach are that interoperable systems are not necessarily required to conduct the suggested analysis. Instead, the same analytical approach could be taken with the different data sets and the results compared to assess the similarities and differences in the data. One specific example would be to perform an audit of the number of bullets, cartridge cases stored by each country and the number of individual firearms they represent. A further task could be to record the make and model of firearms this sample represents. Analysing just these points could yield useful information on the varying ways in which the systems are being used in different countries and also the trends observed in firearms being used to commit crimes. This data when overlaid with data from other sources such as the dates of legislative changes could yield powerful information and intelligence. Despite some of the issues found with ballistics analysis systems by this research, use in this context would show that they can still yield useful intelligence through the data that is being collected in addition to the correlations they are primarily used for. This application of the technology could also be considered in the development of future systems. One such approach would be to ensure that automated reporting functions are included in new technologies.

6.1.5 Supply, Distribution and Trafficking of Firearms

Spapens (2007) highlighted the need to understand the ways in which weapons are trafficked with the aim of preventing and detecting future weapon trafficking offences. Spapens (2007) also pointed out that understanding this problem is made more difficult by the lack of data that is available. One of major barriers to understanding the extent to which weapons travel is the lack of interoperability between ballistics analysis systems. For example, Germany uses the Evofinder system whilst the UK uses the IBIS-Trax 3D system. These systems are not interoperable so data cannot be shared between them. Unfortunately, the results of this Thesis suggest that interoperability between systems A and B is not possible. Logically it would seem that interoperability between other systems is also not possible. Certainly there is firm evidence provided by this Thesis to suggest that interoperability between systems A and B is not possible without the explicit cooperation of the manufacturers. Although there were occasions where there was agreement between the systems and even occasions where the same result was observed, there were also occasions where an opposite result was observed. An example is the result for cartridge case 8A (firing pin impression) where system A correlated object 8B at position 74 and object 8C at position 3. System B however correlated the cartridge cases in the opposite relative order, placing cartridge case 8B at position 1 and cartridge case 8C at position 48. This is just one example of the inconsistencies in correlation results between systems that suggest that interoperable systems are not possible because of fundamental differences in data acquisition and correlation algorithms. Arguably interoperability is one of the most important problems to solve because there is evidence to suggest that there are patterns in firearms supply and consequential use in crimes that cannot be identified due to a lack of interoperability between systems.

Wintemute el al (2004) showed that a small number of retailers account for a disproportionately large number of guns that are used in crimes. Wintemute et al (2004) also showed that guns have a different time to crime[18] that can be detected based on purchasing information. It was suggested by Wintemute et al (2004) that a time to crime of less than three years is suggestive of trafficking. The data analysed by Wintemute et al (2004) was purchase information and then information from when the firearm was recovered using data gathered in a single country – the United States. Replicating this research in Europe would be problematic because once a weapon moves to a country different to where it was purchased, the trail is lost. Even if the firearm was subsequently recovered, test fires produced by it cannot be routinely checked against databases held in countries using other systems. An example is Germany and the Czech Republic which share a border. Germany uses the Evofinder

[18] "Time to crime" is defined as the time from when the weapon is sold to when it is recovered (Wintemute et al, 2004: 733).

system and the Czech Republic use the Balscan system. These systems are not interoperable. Bullets and cartridge cases have to be physically transported between countries to be compared. Occasionally digital images of the samples are emailed between laboratories. This practice was witnessed by the author during a visit to the Czech Republic Police in April 2009. The fact that this practice is carried out shows there are occasions where weapons are used in different countries and also that there is an opportunity to optimise the process of exchanging data.

Data of the type that Wintemute et al (2004) used to identify trends in the United States is not readily available in some European countries. There is no systematic way of querying databases holding forensic ballistics information. One way to address this would be through the development of interoperable ballistics analysis systems and a standard data format. This approach has been suggested before notably by Tulleners (2001:6-3) who stated, "Specifications could be developed that meet the needs of the state database. The image would then be transmitted to the state in full format for further processing by whatever technology the state decides to use. This standard would also leave the original image available for reprocessing should a new vendor with a different algorithm want to enter this field."

6.1.6 Specialist Police Operations

The literature review explained the role that specialist police investigations can play in tackling gun crime. One such example was Operation Trident in London (Metropolitan Police, 2010). Part of the focus of Operation Trident is a focus on disrupting the supply and demand of firearms. Presumably such a remit depends upon information that is available regarding crimes that do occur and the firearms that are used in the commission of these crimes. Ballistics analysis systems do play a part in specialist operations such as Operation Trident. Trident is UK based and the UK uses a ballistics analysis system other than the two examined in this Thesis. However the results of this Thesis still have important implications for specialist operations that may be set up in future in the UK and in other countries. These implications are especially relevant for countries that use the ballistics analysis systems studied in this research.

Spapens (2007) pointed out that there is a lack of data relating to trafficking of firearms before their use in crimes. This must affect specialist police operations with a remit such as that of Operation Trident. Arguably the linkage of crimes through forensic ballistics data may be hindered through a lack of accuracy of some of the current technology. This would make is difficult to know with absolute certainty that either there were no links in a database to a questioned bullet or cartridge case or alternatively that every single link had been discovered. Consider the results of this Thesis where one of the known matches was correlated in the top position and the other at a lower position on the correlation list. One such example is the results for cartridge case 11A for the firing pin algorithm. Both system A and B correlated cartridge case 11B at position one. Cartridge case 11C however was correlated at positions 321 and 335 respectively. A result such as that for cartridge case 11A if replicated in real casework raises the possibility of undiscovered links between crimes. This again is clear evidence that improvements to the technology are needed in the interests of increasing accuracy.

The lack of interoperability between systems may also hinder specialist police operations such as Operation Trident. Suppose that an investigation suggests that weapons are being trafficked from continental Europe to London. There will be some countries in Europe using the same ballistics analysis system as London and the bullets and cartridge cases from seized weapons can be checked against these databases. Other countries that are using different systems will not be able to be checked. The important point is that the lack of interoperability between systems is the driver behind the actions the specialist police operation may take rather than investigatory avenues that have been highlighted as necessary. In practice this would mean that instead of being able to choose which databases are checked based on the investigation to date, the choice is dictated by the technology a particular country may have installed. A lack of interoperable systems also makes the gaining of an overall picture difficult. It may be understood that weapons are being trafficked from Country A to B but the movement of the weapon prior to its arrival in Country A may not be understood or known because the data is not available.

6.1.7 Weapon Registration

Feasibility studies have been carried out to assess the possibility of implementing a weapon registration scheme also known as a reference ballistics imaging database. This would entail all legally purchased firearms being test fired and the bullets and cartridge cases being acquired by a ballistics analysis system so that these bullets and cartridge cases are available to be correlated against samples collected at crime scenes. Tulleners (2001) and De Kinder (2002b) examined the possibility of such a scheme and this work informed a report by Lockyer (2003). The conclusion was that such a scheme was not possible for three reasons. Firstly, the fact that only 5% of weapons used in crimes are legal weapons, secondly, the prohibitive cost and thirdly the fact the technology was not accurate enough. The results of this Thesis do provide some evidence to support the last point regarding technology accuracy. The results showed that system A was able to correlate one of the two known match bullets in the top twenty on 86.96% of occasions and system B achieved a percentage success rate of 69.56%. These percentages dropped to 82.61% and 47.83% respectively when correlating both known matches in the top twenty. Error rates were also defined and calculated. The total error rate percentage was defined as any occasion where the system has not achieved a perfect result and a non-matching object or objects has been presented in a higher position that an actual matching object or objects. If a system failed to produce any results, this would also be regarded as an incorrect result if the matches were present in the database. The total error rate percentage for bullets was 34.78% for system A and 56.52% for system B. For the cartridge case breech face algorithm, the percentages were 50% (system A) and 95.45% (system B). For the firing pin algorithm, the total error rate percentages were 81.82% (system A) and 86.36% (system B). The false positive error rate was defined as any occasion where a non-matching object was correlated in the top position above known matching objects. The bullet false positive error rates were 17.39% for system A and 39.13% for system B. For the cartridge case breech face algorithm the false positive error rate percentages were 27.27% (system A) and 45.45% (system B). For the firing pin algorithm, the false positive error rate percentages were 31.82% (system A) and 27.27% (system B). The findings regarding error rates are problematic when considering a weapon registration scheme. Nennsteil and Rahm (2006a) demonstrated that accuracy decreased as database size increased. Any database housing a weapon registration scheme would be considerably larger than an open case file database. Consequently, the systems would need to be significantly more accurate than they are at present.

A weapon registration scheme may also face legislative and ethical problems. One of the main differences between an open case file of ballistics exhibits and a database of exhibits from legally held weapons is that bullets and cartridge cases from the open case file have been collected from crime scenes. Exhibits in a weapon registration database would represent bullets and cartridge cases fired by weapons owned perfectly legally by innocent people. Presumably there would also be personal information stored that would connect the legally held weapons to the owners. This would raise questions of proportionate use of the data and result in the need for clear policies and procedures in place should the system suggest a cold match[19]. Given the inaccuracy of the technology demonstrated in this Thesis in some conditions, it is entirely likely that innocent people may find themselves under suspicion because of an erroneous result of a ballistics analysis system. Related to this point is the discussion of these results in the context of confirmation bias. Previously work by Kerstholt et al (2010) examined the effect of biasing information of firearms examiners but crucially not with ballistics analysis systems. There has not been any research examining the effect of biased information (the presence of non-matching objects above matching objects on a correlation list for example) generated by ballistics analysis systems. Arguably this issue should be addressed before introducing more complexity into databases of bullets and cartridge cases, and increasing the

[19] A cold match is defined as a link between ballistics objects (bullets or cartridge cases) made solely through the use of a ballistics analysis system. There is no other intelligence or evidence to suggest the match and it has only been uncovered though the correlations carried out by a ballistics analysis system.

resultant workload of ballistics examiners. Similar arguments were made by Cork et al (2008) and the results of this Thesis provide supporting evidence.

Another difficulty relates to the fact that test fired bullets and cartridge cases from legally held weapons would presumably be of good quality as the test fires would be performed under controlled conditions. If legally held weapons were registered at the point of sale it is also likely that a large proportion of weapons would be new and this again would result in good quality striations on test fired bullets and cartridge cases. If weapon registration scheme exhibits and the open case file exhibits were stored in the same database, legally held weapons could erroneously be correlated higher than crime scene samples simply because the quality of the marks is better (Cork et al, 2008).

If a weapon registration scheme was to be introduced, the results of this Thesis and of Tulleners (2001) and De Kinder (2002b) suggest that the technology firstly needs to undergo rigorous feasibility testing. It was described earlier in this Chapter how testing technology can reveal features that are applicable to some laboratories but maybe not others and how testing in a controlled environment would enable transparent procurement decisions to be made. The same argument applies to any technology underlying a weapon registration scheme and is arguably a strict prerequisite to any scheme. It should also be noted that there are practical differences in registering a weapon at the point of sale compared to the point of manufacture. It may be easy to register weapons at the point of manufacture. A device that captured the digital signature of a weapon could be built into the production line. This would enable data that is already collected such as place of manufacture and serial numbers to be associated with the ballistics signature. This could then follow all the legal transactions of the weapon and unlike serial numbers would be difficult to modify or remove. The benefits of registering a weapon at the point of manufacture would be that the cost could be partially or possibly fully covered, by the weapon manufacturer under responsible and ethical business practice legislation. However the one major drawback of such an approach is that it would not cover weapons that are already in circulation. This is where registering weapons at the point of sale may help as second hand weapons would be covered. This would still be problematic due to the vast number of legally held firearms already in circulation (Kopel and Burnett, 2003).

However, it should be noted that despite the various discussion points relating to weapon registration schemes, there is a fundamental issue that prevents implementation of such a scheme. Technology examined to date (Tulleners, 2001; De Kinder, 2002b) and the results of this Thesis suggest that the technology is not accurate enough. Arguably, the only way such a scheme could be introduced would be if technology was improved to the extent where matches were declared with a much higher degree of certainty than is currently the case. It has already been suggested that interoperability of different systems could be achieved if there was an underlying standard for matching bullets and cartridge cases upon which correlation algorithms could be built. A weapon registration scheme would be more realistic if new technologies had an underlying matching standard that enabled matches to be declared to a level of statistical significance in the same way matches between DNA profiles are (Cork et al, 2008).

6.1.8 Alternative Technology that could be applied to Forensic Ballistics

A major issue highlighted by this research has been the accuracy of both technologies examined. The argument has been made that the lack of a matching standard underlying the correlation algorithms has resulted in each manufacturer developing proprietary techniques that make interoperable systems very difficult to achieve despite resultant investigatory advantages. The systems examined in this Thesis are both based upon digital imaging and this directly affects the accuracy of the systems. Bullets and cartridge cases are three dimensional objects but the application of digital imagery to the ballistics field only enables a two dimensional representation of the objects to be captured. Arguably any new technology should be based on approaches that enable a fully three dimensional representation to be captured. Approaches have been suggested by Chu et al, (2010), Banno, (2004), Geradts, (1994), Field, Kelley and McCabe, (1996) and Nor Azura, Choong-Yeun and Abdul Aziz, (2010). An approach based on surface metrology was described by Xie et al (2009). This approach involves the measurement of a bullet using a stylus that touches the objects and captures the topographical profile of the object in three dimensions. Cork et al (2008) suggested that the technology does not allow measurement at sufficient detail. This point is clearly refuted by the work of Xie et al (2009). The application of a measurement stylus to forensic ballistics has also been overlooked and discounted due to the fact that there is physical contact between the stylus and the bullet. However, there is physical contact with bullets and cartridge cases throughout the forensic process currently. Examples include the handling and storage of bullets and cartridge cases. Another example is the marking of bullets with a diamond tipped marker prior to acquisition by IBIS Heritage in Israel (Argaman, Shoshani and Hocherman, 2001). The test firing method can also affect the striations on the bullet yet these contacts do not seem to generate any concern. It is also likely that there is a trade-off between the complete data that can be gained from a bullet and minute potential damage that can be accounted for. The current approach is arguably equally problematic as there is no damage but incomplete data acquisition due to poor or inconsistent lighting issues. The contact between a measurement probe and the bullet could in fact be carefully managed. One approach might be to take a replica of the bullet using casting methods or to also capture the object using another non-contact technology. This would allow any damage to be recorded and explained. The potential for damage is also related to the material of the ammunition with harder materials such as copper much less likely to be damaged than softer metals such as lead.

The application of a contact stylus to ballistics analysis is particularly attractive because it would allow the inside of a barrel to be measured. Currently a bullet to bullet comparison is carried out to ascertain if a certain weapon fired both bullets. The ability to measure a barrel would remove a layer of complexity by allowing direct comparison of objects (the barrel and gun) that have come into contact with each other generating distinguishing marks. It is also possible that barrel measurement would enable a virtual bullet to be created by inverting the digital signature of the barrel. The exact transfer function of the barrel topography to the bullet does however require more research.

Xie et al (2009) concluded by stating that further research is needed using a large number of bullet samples. The application of the methodology designed in this Thesis and the ammunition test set would be ideal to the technology described by Xie et al (2009). The utilisation of the sample of ammunition generated for this Thesis would allow the same bullet to be represented by imaging technology and technology based on 3D surface metrology. This would demonstrate the differences in approach and the additional data that can be gained by 3D measurement. The capturing of measurement data that is a precise representation of a bullet may also contribute to a matching standard. The quality of a match and any associated standard will be determined by the quality of the data. Technology such as that described by Xie et al (2009) has the advantage of offering "complete and accurate bullet surface topography data" (Xie et al, 2009: 522). Once the technology has been assessed and feasibility proven, industrial application is possible.

6.1.9 - Potential Barriers to Innovation

The introduction of new technology into any organisation can problematic often due to the scale of changes required and the difference in working practices that may result. Other technologies used in crime prevention such as ANPR and CCTV have faced similar challenges and the lessons learnt can be applied to any future introduction of new ballistics analysis technologies. Some of these were described in the literature review (Henderson et al, 2004; Gill and Spriggs, 2005).

One of the main barriers to innovation that any technology may face is the lack of interoperability between the new technology and the existing system it may replace. Even if new technology is replacing a manual system there will be a large amount of bullets and cartridge cases that will need to be acquired by a new system. Before the acquisition of bullets and cartridge cases started for this research there were considerable difficulties in organising and planning this research. This represents an important finding in itself because it shows that acquiring large quantities of bullets and cartridge cases onto any system is difficult and time consuming. An alternative approach would be to enable some form of back-record conversion between the incumbent system and the new system. Again, the requirement for interoperable systems is present but as has been previously noted there would need to be cooperation from the manufacturers to enable this to happen which may be unlikely. This again emphasises the need to develop a standard data format that would allow the exchange of data between different systems.

6.2 –Implications

Crimes involving firearms have a significant impact on victims and society as a whole and when they do occur are frequently reported in the media (BBC, 2008, BBC, 2009, BBC, 2010b). The extent of crimes involving firearms varies between countries (Krug et al, 1998; Agozino et al, 2009; Dauvergne and De Socio, 2008; Sheptycki, 2009; Campbell, 2010) and evidence suggests that the incidence of crimes involving firearms is linked to other factors such as availability and legal restrictions on their ownership and possession (Warlow, 2007). There is also evidence to suggest that crimes involving firearms are associated with other types of criminality such as the trade in illicit drugs (Hales et al, 2006). The quantification of gun crime can be problematic due to the fact that victims and witnesses are often reluctant to come forward and forensic evidence can be difficult to obtain. Crimes involving firearms will often go unreported and this can result in a situation where victims and witnesses are not available to be interviewed and forensic evidence cannot be obtained (Squires, 2008).

Ballistics analysis systems are often used in the investigation of gun crime especially to check for links between crimes through ballistics evidence. The use of such systems has led to research being conducted to examine the functionality and performance of these systems with the aims of providing recommendations on best practise and the best way to use these systems (Tulleners, 2001; De Kinder, Tulleners and Thiebaut, 2004; George, 2004a; George 2004b; Brinck, 2008; Nennsteil and Rahm, 2006a; Nennstiel and Rahm 2006b; Braga and Pierce, 2004; Cork et al, 2008). When this Thesis commenced there had not been any research conducted on any system other than the IBIS systems manufactured by Forensic Technology Inc. Other systems that are installed in various countries had not been the subject of published research.

The conclusions and implications of this Thesis can be discussed in the context of four areas. Firstly, the conclusions and implications in relation to interoperable systems, secondly, factors relevant to the usage of the systems by ballistics experts, thirdly, the usage of the systems by police officers and finally issues relevant to the procurement of ballistics analysis systems.

6.2.1 Interoperability of Ballistics Analysis Systems

There was and continues to be no interoperability between ballistics analysis systems manufactured by different providers meaning that data cannot be shared between different systems. This is despite the fact interoperability has been suggested before notably by Tulleners (2001) and Cork et al (2008).Because of the problems faced by law enforcement agencies specific to gun crime, the suggestion was put forward that it is of vital importance to utilise all evidence that is gathered when crimes are reported to police. Furthermore, it was suggested that increased data sharing of forensic ballistics data could generate further intelligence leads but that the lack of interoperability between different ballistics analysis systems was a solid barrier to realising this.

One of the aims of the research was to input the same sample of bullets and cartridge cases to different systems and assess the output to ascertain the potential for interoperability. The results of the experiment clearly show that interoperability is a complex, difficult problem. It may be the case that there are two types of interoperability. Complete interoperability between systems would refer to the ability to freely exchange raw data between different systems and to perform correlations across data from different systems. Another form of interoperability could be the ability to extract and share the correlated data from different systems but without the ability to perform correlations on raw data. This would be a compromise but would at least allow the examination of objects to be partially performed using the systems instead of requesting the physical bullet or cartridge case.

Agreement between systems is an important finding in the context of interoperability because results from systems that are the same or similar suggest that similar underlying principles within the systems are responsible for the results This would suggest that interoperability would be possible because of the underlying similarity in functionality. There were occasions where there was complete agreement between the systems in terms of correlation list positions of the known matching objects. There were also occasions where there was a lesser form of agreement between the systems where the correlation list positions were similar. However there were many occasions where there was clear disagreement between the systems. Disagreement was evident in the form of objects being correlated in different positions but in the same order (object B above object C for both systems) but also objects being correlated in the opposite order. For example there were multiple occasions where system A correlated object B above object C but system B produced the opposite result and correlated object C above object B.

The observed variance in the correlation list positions generated by the two systems examined, show that whilst the physical bullets and cartridge cases were the same, the digital representations of the bullets and cartridge cases captured by each system were different. There were occasions where seemingly opposite results were generated by the systems. For example, system A correlated one bullet above the other and system B placed the bullets in the opposite order. The same type of result was observed for some cartridge cases. Such results would suggest that the correlation algorithms are different. It is likely that the only way in which complete interoperability of systems is possible is with the full cooperation of the manufacturers who would be required to share their data acquisition and correlation techniques with the aim of coming to a consensus based approach as to how interoperability could be achieved. Due to concerns around trade secrets, intellectual property, patents and market share, this seems unlikely to happen.

A compromise would be to develop a series of calibration artefacts which are known test fires that are shared between all manufacturers and are available to test correlation algorithms to ensure minimum error rates such as that proposed by Song et al (2010). This would then allow manufacturers to develop any correlation techniques as long as the minimum performance levels are specified. These so called test fires may be real physical artefacts or in fact could be digital synthetically generated data sets that are widely available to test software correlation algorithms. The development of synthetic data files for algorithm development has been established in the allied field of engineering micro surface metrology where the data files and their relevant characteristics are free to download from National Measurement Institutes such as the National Physical Laboratory in the UK. These data files can then be used as softgauges for algorithm development (Blunt et al, 2008).

To facilitate interoperability of data, a standard data format could be developed to enable the sharing of images and associated data between systems. In this context there would be a clear distinction between the automated correlation and matching functionality of the systems and the image viewing capability of the systems. The standard data format could sit outside of the correlation functionality and simply facilitate the sharing of images to allow experts to make an initial assessment on the similarity of a bullet or cartridge case before requesting the physical sample or transporting the physical sample to another laboratory which could be located anywhere. More importantly a standard data format could allow data to be measured on one system and then electronically transferred to another system from a different manufacturer but still be entered into the correlation database. This would undoubtedly save time and money. This approach would also require the cooperation of the manufacturers in terms of agreeing a standard data format to facilitate data exchange. All that would be required would be development of an export module to allow the high detail images upon which the correlations are carried out to be exported out of the system and inputted into a database. If this approach to interoperability was taken, the development of a database would also be required; storing the images and associated data such as classmarks and case reference numbers to allow the search and retrieval of images based on case data and classmark data. A similar approach has been adopted in the allied field of engineering micro surface measurement where all manufacturers allow data to be transferred into a common data format, .sdf which can be read on any surface measurement system (Blunt and Jiang, 2003).

A further factor related to interoperability is the fact of calibration of the measurement system. For the tested systems A and B, the instruments are not normally calibrated by the end user. Calibration is carried out to ensure the measurements are “correct” and the instrument is not generating measurement error and the measurements are fully traceable. Where instruments are used as standalone systems, this is not necessarily a problem as the results are all relative to each other and not absolute. However, if interoperability is a goal, then absolute instrument calibration will become a serious issue. This will especially be the case if systems move to 3D surface measurement solutions.

The implications of the results are that full interoperability between the systems examined may not be possible without the cooperation of the manufacturers. The results would also suggest that interoperability between other systems is not possible. A more limited form of interoperability may be possible where data can be extracted and shared based on standard data formats. The wider implication is that the barrier to effective data sharing that the lack of interoperability creates, is likely to remain unless there is significant pressure placed on the manufacturers of the technology to innovate in this area. This pressure may have to come from the users of the systems or from legal directives ensuring that some form of standard is implemented, especially where multiple systems are present under one legal jurisdiction.

The wider implication of this research concerns the fact that there is no matching standard for ballistics objects upon which systems and algorithms can be built. This has resulted in proprietary data capture and correlation algorithms that are incompatible with other proprietary data acquisition and correlation algorithms leading to a lack of interoperability. The results of this Thesis imply that further research is needed to address the lack of a matching standard so that it can be applied to existing and new technologies. Arguably, a route to interoperability is new technology built using a standard for matching as the underlying principle. It may be the case that other techniques such as Xie et al (2009) that allow more detailed data capture are more suited to ballistics objects than digital imaging and that the greater level of detail these techniques can capture will enable a matching standard to be developed.

6.2.2 Usage of the system by Ballistics Experts – System Functionality

The results of this Thesis have highlighted factors specific to the usage of the systems by ballistics experts. These findings concern the ways in which the systems can be used more effectively to enhance the value they can add to a laboratory. Secondly, however the results have implications for the interactions between the systems and the experts that use them.

Users of the systems should have an understanding of the ways in which the systems work - including the strengths and weaknesses of a system and any caveats that must be applied to the results. These factors may have an impact on the conclusions of the examiner so should be considered carefully. Two different error rates were defined as part of this Thesis. Both depend on an objective standpoint being taken – the acceptance that the results are either correct (a perfect result) or incorrect (any other occasion). The first error rate, “Total Error Rate Percentage” refers to the occasions where the system produced a result that was incorrect; a perfect result was not achieved. For system A and bullets the error rate percentage was 34.78%. For system B, the error rate percentage was 56.52%. For cartridge cases, the error rate percentages for system A were 50% (breech face algorithm) and 81.82% (firing pin impression). For system B, the error rate percentages were 95.45% (breech face algorithm) and 86.26% (firing pin impression). An alternative error rate percentage was also defined called the “False Positive Error Rate” and the definition of this is any occasion where a non-matching object has been correlated in the top position above the known matching objects. The error rate percentages for system A for this definition were 17.39% (bullets), 27.27% (breech face algorithm) and 31.82% (firing pin algorithm). For system B, the error rate percentages were 39.13% (bullets), 45.45% (breech face algorithm) and 27.27% (firing pin algorithm). These error rate definitions could be used in further research in addition to percentage success rates. The results suggest a need for caution and understanding when interpreting correlation lists and declaring matches. It is also important to understand that a system not suggesting a match does not guarantee there are no matching objects in the database. This should be communicated clearly to the investigating officer to ensure there is no underlying assumption that the questioned object definitely does not match previously seized and examined exhibits.

6.2.3 Usage of the systems by Ballistics Experts – Effect of Ammunition Type

There were occasions where one cartridge case was correlated in a relatively high position and the other was correlated at a much lower position. It was suggested that the ammunition type may be affecting the results and consequently this was investigated further. The results combined with the type of ammunition suggest that this is an important variable and that both systems were more successful at correlating cartridge cases that were the same ammunition type as the cartridge case in question - this probably being a material property variable. This supports the findings of previous research conducted by Nennsteil and Rahm (2006a) and De Kinder, Tulleners and Thiebaut (2004). These findings can be translated into practical recommendations such as ensuring that samples uploaded to ballistics analysis systems are of the same ammunition type as samples already on the database. This approach has been suggested by Nennsteil and Rahm (2006a) and Argaman, Shoshani and Hocherman (2001).There is, however, a trade-off to be made between this and ensuring the database is not too large. Research has suggested that the performance of ballistics analysis systems decreases as database size increases (Nennsteil and Rahm, 2006a). The tipping point of this trade-off is not fully understood and is perhaps an avenue for further research. The findings in relation to ammunition type again show that the capabilities of a system should be communicated to and clearly understood by the user community.

6.2.4 Usage of the systems by Ballistics Experts – Correlation List Length

The number of objects on the correlation list presented to the user of a system that are actually examined varies between laboratories and countries. Previous research has suggested correlation list lengths of ten objects (IBIS training manual), five objects (Silverwater and Koffman, 2000) between five and ten objects (Nennsteil and Rahm, 2006a) and twenty objects (Brinck, 2008). Most laboratories do not examine objects that fall outside the top twenty on the correlation list. There were results for both systems where the known matches were either correlated outside the top twenty or not at all. The implication of this is that these objects would in all likelihood not be discovered in a real-life situation. This could lead to links between crimes not being discovered despite the evidence being held in the database.

The results of the Thesis and the accompanying discussion demonstrated that there is wide variance in the results in terms of the specific correlation list positions of the known matching objects. However, the results suggested that there is an optimal correlation list length for this particular data set. The implications of this research are that for bullets, and system A the top twenty objects should be examined while for system B it is suggested that the top ten objects are examined as no increase in performance was observed by increasing the correlation list beyond ten objects. For cartridge cases, the results have produced evidence to suggest that the top twenty objects on the correlation list should be examined. The only exception to this is for the breech face algorithm of System B. No improvement in success rate was observed by extending the list beyond two objects although it should be noted that the success rate overall for this condition was low. The implication of the experimental work is that given a particular data set, ideal and realistic standards can be developed. Ammunition type of uploaded samples and the number of objects examined on a correlation list are two examples. These standards may only be applicable to a particular laboratory but may increase efficiency if researched and applied carefully.

6.2.5 - Use of the systems by Ballistics Experts - Confirmation Bias and Subjectivity

The investigation of crimes involving firearms often involves experts presenting evidence in court that two objects (bullets or cartridge cases) match and have therefore been fired from the same weapon (Nichols, 1997). There are however different working practices and procedures that form the process of arriving at a declared evidential match (Schwarz, 2004). For example, there may be occasions when a bullet has been recovered from a crime scene along with a weapon. In this case, the bullet will be compared with a test fired bullet from the recovered weapon to ascertain whether or not the two objects match. In some cases however, a bullet or cartridge case will be recovered from a crime scene and there will be no weapon to compare it to. In these circumstances, it is likely that an automated system will be used to ascertain if the object has any matches in the database and consequently if any crimes may have been committed previously using the same firearm.

In this Thesis, an automated system obtained a perfect result when both known matching objects were correlated in the top two positions. For the bullet condition, system A achieved a perfect result percentage score of 65.22% and system B achieved a perfect result percentage score of 43.48%. The implication of this is that when examining the results for the twenty two test objects, there were 34.78% and 56.52% of occasions respectively when a perfect result was not achieved and objects that are known non matches were presented in a higher position on the correlation list that the actual known matching objects. This was defined as the Total Error Rate. This immediately raises the possibility that because there are known matching objects being presented to the user of the systems as being more similar than actual matching objects, confirmation bias may be inherent in the use of these systems.

Kerstholt et al (2010) examined the possibility that firearms examiners may be affected by confirmation bias and concluded that the biased information did not affect the conclusions of the examiners. However, there were methodological issues with the study such as the fact there was not a control condition and the participants were aware they were participating in an experiment. The participants in the study conducted by Kerstholt et al (2010) were also only given two bullets to examine with no information provided about their relative similarity to another object. There has not been any research conducted that examines the potential for confirmation bias when an expert is using an automated system to generate a list of potential matches. The results obtained as part of this Thesis show that on some occasions, the automated systems rank non matching objects as more similar the actual matching objects. The extent to which this information may mislead an examiner into declaring a match wrongly is not understood and requires further research to ascertain the extent to which these false positives could bias the conclusions of firearms examiners. Arguably further research should be treated as a priority given the challenges the discipline is currently facing (Schwarz, 2004; Schwarz 2007; Edwards, Gatsonis and Kafadar, 2009).

The results of this Thesis suggest there are implications when a cold hit is suggested. A cold hit refers to an occasion where a ballistics analysis system suggests a match to another object (and therefore another crime) in the absence of any other evidence. Caution should be applied on these occasions. It may be the case that upon further investigation of a cold hit, evidence is gathered to confirm the link. Alternatively it may be the case that no confirmatory evidence is found. It is in these cases that caution should apply.

When a match is declared based on a correlation from an automated system, in many jurisdictions, it may be the case that the involvement of a ballistics analysis system is not presented in court. Instead the ballistics evidence would be presented as a match between two objects in the experience and judgement of the examiner. Perhaps an implication of this research is that the process by which a match is arrived at should also be presented in court along with the functional intricacies of the ballistics analysis systems. It may also be the case that in some jurisdictions ballistics evidence is not admissible in the absence of other evidence whilst in other jurisdictions ballistics evidence is admissible in isolation. Consider a situation where a cold hit suggests a link to another case and a potential suspect. Upon investigation of this link, a positive DNA profile is gathered between the outstanding DNA profile in the current case and the suspect suggested by the cold hit. Clearly, this is valuable intelligence that has resulted in the detection of an offence. The results of this Thesis imply that in the absence of the DNA evidence, the ballistics evidence may have been questionable because of the potential for confirmation bias. It may be the case that the impact is negligible but the key point is that there is a clear lack of evidence supporting either side of the argument. This lack of evidence may result in the use of valuable intelligence being hindered. Research has suggested that ballistics experts are aware of the issue of confirmation bias (Burns, 2001). It is arguably in the interests of the ballistics expert community to undertake further research to demonstrate that evidence that has involved the use of ballistics analysis systems is reliable.

In response to criticisms of the forensic ballistics discipline, experts often point out that they undergo proficiency testing (Nichols, 2007). There is however a clear difference between proficiency testing and confirmation bias. Proficiency testing does not involve examiners being presented with deliberately biased information. Neither does it necessarily involve controlled conditions so the impact of biasing information cannot be assessed. Proficiency testing can also involve scenarios that are simpler that real life cases (Schwarz, 2007). It has also been suggested that examiners perform better in proficiency tests that they do day-to-day (Schwarz, 2004). A further implication of the current research presented in this Thesis is that there is a case for developing a proficiency test that incorporates biasing information. This would allow the impact of the biasing information to be assessed.

The results of the experimental work have clearly demonstrated that there is wide overall variance in the results produced by the two different systems examined – even when comparing the same classmark type (breech face or firing pin impression). Whilst there was agreement and disagreement between systems, perhaps more striking, were the occasions when there was disagreement between the systems in terms of the relative ranking of objects. For example when system A correlated one object above another, system B placed the same objects in the opposite relative positions. Objectively both results cannot be true. An objective scientific procedure would rank one object above another consistently. A result of this type is not altogether unsurprising however as there are no set standards for the identification of bullets and cartridge cases despite attempts (Bunch, 2000; Song et al 2009; Chumbley, et al, 2010; Saks, 2010). The results obtained demonstrate that because of the lack of standards for identification and comparison, each manufacturer has devised their own algorithms. If the assumption that the expert is in any way influenced by the results presented by a system is taken to be true, then a system presenting one result and another system presenting the opposite result introduces some concerning issues for the discipline of forensic ballistics science.

A further implication of this Thesis for the ballistics expert community concerns the examination, publication and verification of research conducted on ballistics analysis systems. Previous research has been conducted independently without the sole involvement of the manufacturers (Tulleners; 2001, De Kinder, Tulleners and Thiebaut, 2004; George, 2004a and George, 2004) whilst other research has involved the manufacturers of the technology (Roberge and Beauchamp, 2006; Brinck, 2008). This Thesis has demonstrated the value of a test set of ammunition that is available for use with any system and is also available for independent validation. An implication is that any future research whether carried out independently or by a manufacturer should have all data including the ammunition samples available for inspection, validation and replication by other interested parties. This would ensure that the reliability of the findings.

6.2.6 Use of Ballistics Analysis Systems by Police

There are also conclusions and implications on issues relevant to policing practise. The lack of interoperability between different systems also results in a situation whereby the ability to pursue investigatory leads through ballistics data is hindered. An ideal situation would be if any database could be searched depending on investigatory need rather than on technology type. Spapens (2007) noted that there is a lack of evidence relating to the trafficking of firearms. Trafficking is by nature a cross border problem so arguably interoperable systems would at least enable searches to be performed routinely. However currently, this is dependent on the technology a particular country has installed. This has an impact on police investigations aimed at understanding, documenting and ultimately disrupting the illegal supply of firearms such as Operation Trident (Robert and Innes, 2009) and Operation Ceasefire (Kennedy, Braga and Piehl, 2001). Whilst Operation Trident and Operation Ceasefire were focussed on relatively small geographical areas (London and Boston respectively) the argument in relation to trafficking still applies because weapons did arrive in these cities from other locations.

Data held on ballistics analysis systems could also be used by police operations such as Trident and Ceasefire even when weapons are not fired. Take for example a situation where a gun is used to threaten a victim and whilst the weapon is not fired, the victim may recall the weapon in detail. This description may lead a ballistics examiner to conclude the weapon was of a particular make or model. Searches could then be performed using an automated system as these systems are more likely to have details on weapons more accurately described that police crime reporting systems. This is because information recorded on ballistics analysis in entered by domain experts whereas the crime report will often be completed by a police expert. Searches such as this when combined with other intelligence may result in a list of potential linked crimes and suspects. Whilst this approach in a relatively small geographical area such as a city may not be problematic, extending this search to other countries may prove difficult because of the lack of interoperability between systems.

A further implication of this is that data routinely captured by ballistics analysis systems could be used to generate intelligence on firearm trends and crime types. A similar approach has been applied in the UK (Hannam, 2010). This Thesis has provided evidence to suggest that the trends observed in firearms usage can be identified in the data captured by ballistics analysis systems because details regarding calibre, ammunition and other defining features are required by correlation algorithms. This data could be assessed without the need for interoperable systems and then compared between systems to identify patterns in firearms use. Data could also be used to complement official statistics providing a fuller picture as to the extent of gun crime. This approach would have a positive impact on the police investigation of gun crime as it would enable a greater understanding of the problem. This type of data would complement research conducted previously such as that by Smith et al, (2010), Wintemute et al, (2004) and Warlow, (1997).

Research conducted examining the nature and characteristics of crimes involving firearms have demonstrated the high impact these crimes have both on the victim and the wider community (Pershad et al, 2005; Cutts, Bridle and Bleetman, 2006). Crimes involving firearms can also be difficult to investigate due to the fact that gangs and other forms of criminality are often involved (Vaughan et al, 1996; Bullock and Tilley, 2002; Decker and Curry, 2002; Marshall, Webb and Tilley, 2005; Hales et al, 2006; Hayden et al, 2008 and Hallsworth and Silverstone, 2009). Consequently, any improvements to the forensic ballistics discipline that lead to evidence and intelligence being returned to the investigating officer faster could help the investigation of gun crime. The implication of the research conducted for this Thesis is that through the examination of ballistics analysis systems and the consequential understanding of the functionality and usage of these systems, recommendations can be made and applied that may reduce the time taken to return information for the investigating officer.

6.2.7 Procurement of Ballistics Analysis Systems

The nature and characteristics of gun crime varies dramatically between and sometimes within countries (Krug el al, 1998; Agozino et al, 2009; Dauvergne and De Socio, 2008; Sheptycki, 2009; Campbell, 2010). It is therefore logical to suggest that there should be varying responses to gun crime in terms of resources, tools, forensic equipment and policies. This has been demonstrated by specialist police operations targeting gun crime notably Operation Ceasefire in Boston (Kennedy, Braga and Piehl, 2001) and Los Angeles (Gonzales, Henke and Hart, 2005), and Operation Trident in London (Robert and Innes, 2009). A further point of variance in the response to gun crime may be the specification of the ballistics analysis system installed in a particular country or city. Previous research has shown that automated ballistics analysis systems can have a significant impact (Braga and Pierce, 2004). As different locations have different types of problems, some features of particular technologies will be particularly relevant with others not so. This Thesis has provided good evidence that these features of different technologies can be documented and understood. Furthermore a coherent argument has been made to use data gathered from research such as that conducted in this Thesis to inform procurement decisions relating to ballistics analysis systems.

Arguably, the lack of research examining ballistics analysis systems impacts on procurement decisions. Before research for this Thesis commenced, there had only been research conducted on systems provided by one manufacturer (Tulleners, 2001; De Kinder, Tulleners and Thiebaut, 2004; George, 2004a; George 2004b; Brinck, 2008; Nennsteil and Rahm, 2006a; Nennstiel and Rahm 2006b; Braga and Pierce, 2004; Cork et al, 2008). The implication of no interoperability between different systems is that procurement decisions are often a political decision taken by non-ballistics experts. The disadvantages of political procurement decisions have been highlighted with other technologies notably CCTV (Fay, 1998). Often a decision may be taken for an entire country to enable a national database to be implemented. The lack of interoperability between different systems means that laboratories cannot choose a system most suited to their specific needs and access data from another system type in a different city or region. The implication of the research conducted in this Thesis is that whilst research such as this can highlight differences in functionality, the lack of interoperability creates a barrier to truly effective procurement decisions. This is likely to become a more significant issue because of recent alternative techniques and systems that have been suggested (Xie et al, 2009; Chu et al, 2010; Nor Azura, Choong-Yeun and Abdul Aziz; 2010; Barrett, Tajbakhsh and Warren, 2011).

Consider a laboratory that has a small workload. They may be content to procure a cheaper system that takes longer to acquire samples. Conversely a laboratory that has a high workload may prefer to install a more expensive system that acquires samples faster. Another example relating to the accuracy of systems could be a country with a large number of objects that would require a high level of accuracy due to the large number of objects in the database and the number of correlations that need to be performed. Contrast this with a country with a smaller number of objects. Accuracy may be of less importance because the correlation lists are smaller due to the smaller database size. The lack of time constraints also mean that more objects can be physically examined. In this scenario the ballistics analysis system may be used more as an audit system and a backup rather than the primary tool for generating investigatory leads. The critical point in that despite there being evidence to show differences between countries (Krug et al, 1998; Agozino et al, 2009; Sheptycki, 2009; Campbell, 2010) and a coherent argument made concerning different systems being suitable in different circumstances, the lack of research comparatively analysing ballistics analysis systems means that these logical decisions cannot be made easily and routinely.

Considering the differences within a single country, consolidates the argument further. Take Country A as an example. All the ballistics analysis systems installed in this country are provided by a single manufacturer, are linked to a single national database but are significantly expensive. The time taken to acquire a bullet is relatively fast at approximately ten minutes. If a bullet is acquired by a system in City A it will correlated against bullets acquired in City B and City C. There are currently three cities where ballistics analysis systems are installed in Country A. There is a known backlog of bullets and cartridge cases to be acquired to the national database of Country A. The three cities were chosen to house ballistics analysis systems as these were the cities with the highest rates of gun crime.

There are other locations in Country A such as City D where gun crime does occur but in lower frequencies. It may be the case that the purchase of a ballistics analysis system cannot be justified on cost grounds because it is so expensive. However, a significantly cheaper system could be justified because it would enable the smaller number of locally recovered bullets and cartridge cases to be acquired and analysed without submission to the three main centres. The cheaper system may take twenty minutes instead of ten minutes to acquire a bullet but this is acceptable because this particular location does not have a backlog of bullets and cartridge cases. In this situation the cheaper system would enable the acquisition and correlation of locally recovered bullets and cartridge cases providing intelligence concerning potential local links between crimes to the investigating officer faster.

A further implication of the results relates to procurement decisions and the type of object a laboratory may examine (bullets or cartridge cases). Considering the success rate of finding one out of the two known matches on a correlation list of twenty objects, system A achieved a bullet success rate of 86.96%. System B achieved a success rate of 69.56%. The success rates for the cartridge case firing pin impression were the same for both systems at 86.36%. These results imply that success rates combined with other factors such as the cost of the systems and acquisition time are powerful information to a person or organisation making a procurement decision. In the above described example, a laboratory that conducts very few bullet examinations might opt for a cheaper system that performs less well with bullets but is equal to the more expensive system that performs to a similar level with cartridge cases[20]. The above scenario could be considered an adaptation of evidence-based policy implementation described by Bullock and Tilley (2009) and Tilley (2010). A rigorous scientific and evidence based approach to technology adoption and installation has ensured success with other technologies such as CCTV (Waples and Gill, 2006; Welsh and Farrington, 2009; Farrington et al, 2007 and Waples, Gill and Fisher, 2009) and ANPR (Henderson et al, 2004). It can be argued that in the forensic ballistics arena the application of an evidence based approach as to the most appropriate technology to procure is lacking.

6.2.8 Summary of Conclusions and Implications

To conclude, the findings of this Thesis can be grouped into four areas. The first concerns interoperability. The results of this Thesis provide evidence suggesting that interoperability is not possible between the ballistics analysis systems examined because the variance in the results is simply too great. In order to progress towards interoperability, arguably the manufacturers of the technology will need to be engaged. A limited form of interoperability may be possible focussing on sharing data rather than cross correlating between data from different technologies.

The second set of findings concerns the usage of the systems by ballistics experts and recommendations can be made regarding the usage of them. In particular, the findings concerning correlation list length and ammunition type can be applied to the real-life usage of these systems. The results of this Thesis raise the issue of confirmation bias in the discipline of forensic ballistics. The results indicated that there were multiple occasions where non-matching objects were being ranked as more similar than known matching objects. It is not known the extent to which the presence of these objects may affect the conclusions of an examiner. It is also clear that the lack of a matching standard has resulted in manufacturers of the systems devising proprietary algorithms and

[20] It should be noted that the example described here is not representative of the true cost of system A and system B. It merely serves as an example of the types of decisions that could be made if this approach was taken.

correlation techniques. Arguably, optimisation of technology is interlinked with the creation of a matching standard. It may be the case that technology based on principles alternative to digital imaging is required.

The third set of findings relate to the ways in which the results from such systems are used by police officers. The data also suggests that the lack of accuracy of the systems could potentially negatively impact on the police investigation of gun crime by increasing the time taken to return evidence and intelligence back to the investigating officer. An examination of the two systems also demonstrated the implications for policing practise particularly in relation to understanding the supply and distribution of firearms. This is relevant for specialist operations that aim to disrupt this supply. Some of the inaccuracies of the technology combined with a lack of interoperability mean that understanding a complete picture of the problem is difficult. Consequently it is difficult to apply effective interventions.

The fourth set of findings relate to procurement of systems, system specification and the most appropriate response to gun crime. Particular features relating to a system may be more appropriate for a particular manifestation of gun crime in a particular location. This Thesis has demonstrated that valuable data can be gathered by assessing a system and this should be used to inform procurement decisions. Such an approach would increase the potential for ballistics analysis systems to have a positive impact on the police investigation of gun crime and increase the monetary value of these systems to law enforcement.

6.3 - Contributions to the Field

Previous research concerning ballistics analysis systems had at the time of writing been based on technology provided by one supplier and had utilised a variety of methods to examine the technologies from different standpoints. Although previous research had been conducted examining the same technology, there was considerable difficulty comparing the output research conducted under different conditions. This was acknowledged by Nennstiel and Rahm (2006a:18) who stated;

> *"Extensive IBIS instrument tests have been conducted in the past with different goals in connection with these and other studies. Their results, standing alone, however, are difficult to compare with each other. A systematic summary is lacking to determine which parameters have an influence on the success or error rate, respectively, during the operation of the IBIS system."*

Nennsteil and Rahm (2006a and 2006b) addressed this issue through the design of a study to enable the description of the different parameters that affect the success and error rate for the IBIS systems. This Thesis has extended this research through the design of a methodology to enable the assessment of ballistics analysis technologies regardless of manufacturer or underlying technological principles. Before this Thesis commenced, there had never been any published research conducted globally with ballistics analysis technologies other than IBIS Heritage and IBIS Trax 3D. There had also never been a comparative assessment of more than one technology using the same set of ammunition. The Thesis has also produced a measureable contribution to knowledge as the test set of ammunition was designed to enable future research to be conducted and then discussed alongside the research already conducted for this Thesis. Furthermore, a multidisciplinary approach has been taken to the research, placing the forensic process discussed firmly in the context of wider policing issues. This has enabled the results to be relevant in terms of real life policing situations relating to the investigation of gun crime.

6.4 - Methodological Reflections

The methodology employed in this Thesis was complicated to design and implement. After analysing the results and with the benefit of hindsight there are, however, some elements which could have been completed differently. One of the findings concerned the type of ammunition and that the systems were more likely to correlate ammunition of the same type as the object in question above ammunition of a different type. With this point in mind, it may have been more appropriate had the database contained objects that were all of the same ammunition type. However the test fires were performed by various individuals located in various laboratories across Europe. When designing the methodology it was not considered practical to impose a tight restriction on the ammunition type. Instead the focus was on generating a large enough experimental sample. The bullets that were generated for the experimental sample were sent to the author without any indication of the ammunition type. It would have been better if there had been an instruction given to the person conducting the test firing to record the ammunition type used. However, the usage of different ammunition types does reflect the differing ammunition that would be present in an open case file.

A potentially contentious point relating to the employed methodology is the choice of operator for each system. It was recognised in the methodology and in the discussion of the results that the different operators of each system could have contributed towards the observed variance in the results. However steps were taken in an attempt to limit the impact of the operator mainly by placing responsibility for the choice of operator with each manufacturer. Observed variance was also greater in both cartridge case conditions than in the bullet condition despite the fact that there is more input required from the operator and consequently potential for differentiation when inputting bullets. The choice of operator is a key variable and the methodology can theoretically be applied to any system. Therefore it is arguably an advantage of the experimental design that the operator of each system should be different but chosen by the manufacturer. It is doubtful that there is a suitably qualified person who could have operated both systems examined in this Thesis. If other manufacturers participate in similar research in future, using this methodology, there will be even less scope for a single person to undertake object entry on each system. The choice of a different operator chosen by each manufacturer ensures repeatability of the experiment that would not be possible should the operator choice be restricted to a single person across all examined systems.

In an ideal world, every company that manufactures ballistics analysis technology would have participated and each manufacturer was indeed approached with this aim in mind when the research for the Thesis commenced. However, it became clear very early in the research process that not every manufacturer would take part. The main concern was around the confidentiality of the results and any potential commercial impact the results may have on sales. The negotiations with the various manufacturers were at times difficult and protracted. However, as identified in the methodology, an experiment of this nature had not been carried out before with one of the main reasons being the logistical difficulties. As time progressed reluctance on the part of the manufacturers to participate meant that there was a very real possibility that none of the manufacturers would participate. Fortunately a compromise was reached with the two companies that did eventually participate. The compromise included confidentiality agreements and an agreement to not identify which system was which in the Thesis.

There were also various logistical difficulties that arose simply because of the nature of the experimental research, the main one being the cost of participating in such an experiment. None of the manufacturers of this equipment were located near to the site where the experiment took place so the systems had to be transported to Germany where the laboratory was located. An operator of each system also had to be provided by each manufacturer again at the cost of the manufacturer. The time taken to upload the sample of cartridge cases and bullets was lengthy taking between one and six weeks. Obviously the presence of the author was required at various times as the experiment was taking place and this resulted in multiple trips to Germany. However, one of the main aims of the experiment was to control as many variables as possible and it was therefore decided that the location would remain the same for each company. The author is extremely grateful to the two companies that participated in the experiment as the Thesis would have taken a dramatically different shape without their help, cooperation and guidance.

6.5 - Future Research

As has previously been noted, an experiment of this type has not been carried out before therefore there is scope for further research. The most obvious area for furthering the research in this Thesis is to conduct the experiment with the other technology providers. Whilst they were all visited as part of the current research, on demonstrating the results and benefits of the experiment to date, it is possible that the other manufacturers may be keen to participate in future. Such research would enable a greater understanding of the other systems available and whether or not interoperability is possible between the systems that did not take part. It would be of great benefit to the forensic ballistics community if the market leading technology could be examined using the test set of ammunition generated for this Thesis. A way to facilitate this might be to adapt the methodology to enable the safe transportation of the test set of ammunition to different locations. Alternatively an end user could allow access to equipment providing they could allow enough time for access.

The results and discussion highlighted the fact that the systems examined in the current research are not completely accurate and have high error rates in some circumstances. There is therefore a need to look at other areas of technology and science away from digital imaging where new developments in the forensic ballistics field are occurring. A new system has been developed by Xie et al (2009) based on surface metrology. It would be of great interest to conduct the experiment described in this Thesis with new technologies. It is also probable that the results from such an experiment could contribute to the debate on a matching standard. As they capture objects in three dimensions this would allow a much greater level of detail to be gained.

The results obtained from this Thesis and from previous research suggest that the application of ballistics imaging technology to weapon registration schemes is not feasible as the technology does not perform to a high enough standard. A possible area for further research could be the application of new technologies such as those developed by Barrett, Tajbakhsh and Warren (2011) and Xie et al (2009) to a weapon registration scheme. A pre-requisite would, however, be an understanding of the capabilities of any system.

The results also indicated that there were occasions where false positives were presented to the user. It would of great interest to design and conduct an experiment similar to that carried out by Kerstholt et al (2010) on confirmation bias to ascertain the extent to which the results generated by automated systems affect the conclusions of examiners.

The results suggested that the only way in which complete interoperability would be possible would be with the full cooperation of the manufacturers. Further research could take the form of a working group set up to address this specific question.

Appendix 1 – Full Results

A.1 – Results for Known Match Bullets

This Appendix presents the full results that were obtained from the experimental research described in detail in Chapter four. The results for the bullet comparison are presented first followed by the results for the cartridge case condition. The results are also colour coded throughout. Blue signifies system A and red signifies system B. It is important to note that correlation scores are referred to but these scores are not traditional correlation coefficients and they are not measures of statistical significance. Instead these correlation scores are generated by the proprietary algorithms of each system. These scores are then used to generate the correlation lists and rank the objects and are therefore relative to each system.

For the bullet comparison, each test weapon has three bullets in the database. For example, test index 1A has two matching objects in the database – 1B and 1C. Object 1B is the known matching bullets number 1 (KM1) and object 1C is the known matching bullet number 2 (KM2). The correlation list for object 1A was examined to ascertain where objects 1B and 1C were found. This was repeated for each of the 23 test objects (objects 1A through to object 23A).

Table A-1 shows the correlation list position and the correlation scores for the 23 test objects in the bullet condition. This table shows the results for system A and system B and presents the raw data.

Table A-1: Bullet Results Matrix for System A and System B

KNOWN MATCH 1						KNOWN MATCH 2				
Test Index	Known Match Object (1)	System A Position (KM1)	System B Position (KM2)	System A Corr Score (KM1)	System B Corr Score (KM1)	Known Match Object (2)	System A Position (KM2)	System B Position (KM2)	System A Corr Score (KM2)	System B Corr Score (KM2)
1A	1B	1	1	0.6589	0.337	1C	2		0.4234	
2A	2B	2	1	0.4891	0.078	2C	1	8	0.5274	0.003
3A	3B	1	2	0.5357	0.354	3C	2	1	0.5119	0.622
4A	4B	2	1	0.5031	0.698	4C	1	2	0.5618	0.302
5A	5B	1	1	0.7504	0.448	5C	2	2	0.7014	0.427
6A	6B	2	2	0.5511	0.026	6C	1	1	0.5571	0.061
7A	7B	1	1	0.6619	0.043	7C	2		0.4566	
8A	8B	2	2	0.6568	0.456	8C	1	1	0.7044	0.487
9A	9B	1	1	0.777	0.385	9C	2	2	0.7416	0.038
10A	10B					10C				
11A	11B	1	1	0.7162	0.561	11C	2	2	0.6709	0.333
12A	12B	1		0.3935		12C	17		0.3098	
13A	13B	1		0.617		13C	2	3	0.4037	0.041
14A	14B	1		0.7087		14C	2	8	0.5837	0.018
15A	15B	2		0.4722		15C	20		0.3897	
16A	16B	1	1	0.6912	0.665	16C	2	2	0.6074	0.538
17A	17B	57		0.3418		17C	107		0.3255	
18A	18B	1	1	0.6983	0.331	18C	2	2	0.5936	0.169
19A	19B	1		0.5298		19C	6		0.4246	
20A	20B	78		0.3424		20C				
21A	21B	6		0.4057		21C	11	10	0.3966	0.018
22A	22B	2	2	0.7855	1	22C	1	1	0.8258	1
23A	23B	1		0.4694		23C	37		0.373	

Object 1A – System A achieved a perfect result correlating object 1B in position 1 and object 1C in position 2. System B also correlated object 1B in position 1 but did not correlate object 1C. The correlation list produced by system B for object 1A consisted of 17 objects so this could be regarded as the system suggesting that 16 objects are more similar than object 1C which was not correlated at all.

Object 2A – System A achieved a perfect result correlating object 2B in position 2 and object 2C in position 1. System B correlated object 2B in position 1 and object 2C in position 8. This result shows that system B has presented 6 objects that do not match the test object in a higher position on the correlation list than the actual matching object 2C. System A correlated object 2B in a lower position (number 2) than object 2C (number 1). The opposite result has been found for system B which found object 2B in a higher position (number 2) than object 2C (number 8) .

Object 3A – System A achieved a perfect result as did system B but the results are of interest because the objects are placed in different positions for each system. Object 3B has been placed in position 1 for system A and position 2 for system B. Object 3C has been placed in position 2 for system A and position 1 for system B.

Object 4A – System A achieved a perfect result as did system B but as was the case with object 3A, the actual objects are placed in different positions for each system. Object 4B has been placed in position 2 for system A and position 1 for system B. Object 4C has been placed in position 1 for system A and position 2 for system B.

Object 5A – System A achieved a perfect result as did system B and the objects were correlated in the same relative positions.

Object 6A – System A achieved a perfect result as did system B and the objects were correlated in the same relative positions.

Object 7A – System A achieved a perfect result whilst system B correlated object 7B in position 1 whilst object 7C has not been correlated at all. The total correlation list length produced by system B for object 7A consisted of 14 objects. This could be interpreted as the system suggesting that 13 objects are more similar than object 7C which has not been correlated at all.

Object 8A – System A achieved a perfect result as did system B and the objects were correlated in the same relative positions.

Object 9A – System A achieved a perfect result as did system B and the objects were correlated in the same relative positions.

Object 10A – Neither system managed to produce a result for object 10A. Not only were the known matching objects not correlated but both systems did not produce a correlation list at all.

Object 11A – System A achieved a perfect result as did system B and the objects were correlated in the same relative positions.

Object 12A – System A correlated object 12B in position 1 whilst object 12C was correlated in the seventeenth position. This result shows that system A presented 15 non matching objects as being more similar than actual matching object 12C. System B correlated neither object. System B only returned a correlation list containing a single object for test object 12A suggesting that the system has returned a single non-matching object as a suggested match.

Object 13A – System A achieved a perfect result correlating both known matches in positions 1 and 2 (object 13B in position 1 and object 13C in position 2). System B did not correlate object 13B whilst object 13C has been correlated in position number 3. This result is interesting because object 13C has been correlated by system B in a higher position on the correlation list than object 13B. There were two non-matching objects that were also presented above object 13C. The correlation list produced by system B for object 13A consisted of 9 objects meaning that below the third position, 6 objects were correlated as being more similar than object 13B which was not correlated at all.

Object 14A – System A achieved a perfect result. System B did not correlate object 14B whilst object 14C has been correlated by system B in position number 8. This result is similar to that for object 13A because object 14C has been correlated in a relatively high position on the correlation list but there are seven non-matching objects above the actual matching object 14C that have also been presented. The total correlation list length for object 14A consisted of 15 objects so 7 objects have been correlated as being more similar to the test object than the actual matching object (14B) which does not appear on the list.

Object 15A – System A has correlated object 15B in position number 2 whilst object 15C has been correlated in position 20. For system A, eighteen objects that did not match the object under examination were presented as more similar that the actual matching objects. System B has not managed to correlate either matching object. The correlation list produced for system A for object 15A consisted of 11 objects so the system has presented 11 non-matching objects as being more similar than the actual matching objects. System A presented 18 objects higher than object 15C that did not match test object 15A. The other key point is that system A correlated object 15B in position 2 meaning that a single non-matching object was presented in the number 1 position.

Object 16A – System A achieved a perfect result as did system B and the objects were correlated in the same relative positions.

Object 17A –System A has found both matching objects (17B at position 57 and 17C at position 107) system B has not found either match. The key differentiating point between the systems for object 17A is that system A has presented 105 objects as being more similar than the matching objects whilst the total correlation list presented by system B consisted of just four objects.

Object 18A – System A achieved a perfect result as did system B and the objects were correlated in the same relative positions.

Object 19A – System A has correlated object 19B in position number 1 whilst object 19C has been correlated in position 6 meaning that 4 non matching objects are considered to be more similar than the actual match. System B has not managed to correlate either matching object. System B however produced a correlation list only containing only 3 non-matching objects.

Object 20A – The result for object 20A is of interest because it is the only occasion where system A has correlated only one of the matching objects. System A has correlated object 20B at position 78 and has not correlated object 20C. Seventy seven objects non matching objects have been presented by system A as being more similar than actual matching object 20B. The total correlation list length for object 20A was 186 objects; therefore as object 20C is not on the list at all, the remaining 108 objects on the list below 78th position can also be regarded as non matches that have been correlated higher than the actual matching object 20C as object 20C does not appear on the list at all. System B has correlated neither object. System B however produced a correlation list consisting of only 10 objects.

Object 21A – System A has correlated object 21B (in position 6) higher than object 21C (in position 11) whilst system B has correlated object 21C (in position 10) higher than object 21B (not correlated) System A has suggested 9 non-matching objects as being more similar to the actual matching objects whilst system B has suggested 16 non-matching objects that are more similar than the actual matching objects.

Object 22A – System A achieved a perfect result as did system B and the objects were correlated in the same positions.

Object 23A - System A has correlated object 23B in position number 1 whilst object 23C has been correlated in position 37. System A presented 35 non-matching objects higher than object 23C that did not match test object 23A. System B has not managed to correlate either matching object but produced a correlation list containing only 10 non-matching objects.

A.2 – Results for Known Match Cartridge Cases (Breech Face Algorithm)

This section of the Appendix presents the cartridge case results. For the cartridge case condition, each test weapon has three cartridge cases in the database. For example, test object index 1A has two matching objects in the database – 1B and 1C. Object 1B is the known matching cartridge case number 1 (KM1) and object 1C is the known matching cartridge case number 2 (KM2). The correlation list for object 1A was examined to ascertain where objects 1B and 1C were found. This was repeated for each of the 22 test objects (objects 1A through to object 22A).

Both systems have two different algorithms that can be used to correlate cartridge cases. The first algorithm examines the breech face impression and the second algorithm examines the firing pin impression. The results are presented separately for each algorithm.

Table A-2: Cartridge Case Results Matrix for System A and System B (Breech Face Impression)

	KNOWN MATCH 1					KNOWN MATCH 2				
Test Index	Known Match Object (1)	Sys A P KM1 BF	Sys B P KM1 BF	Sys A Corr Score KM1 BF	Sys B Corr Score KM1 BF	Known Match Object (2)	Sys A P KM2 BF	Sys B P KM2 BF2	Sys A Corr Score KM2 BF	Sys B Corr Score KM2 BF
1A	1B	1	1	0.620172	0.8495	1C	2	2	0.591714	0.8366
2A	2B	1	1	0.629938	1.0	2C	2	44	0.615198	0.7225
3A	3B	1	1	0.60322	0.8367	3C	2	202	0.449516	0.5248
4A	4B	34	363	0.32166	0.2283	4C	45	33	0.308553	0.5648
5A	5B	1	13	0.426917	0.5149	5C	10	217	0.354803	0.4002
6A	6B	1	47	0.417563	0.4084	6C	95	1	0.214954	0.5784
7A	7B	2	268	0.429603	0.3434	7C	13	109	0.392569	0.5652
8A	8B	5	220	0.365545	0.3986	8C	31	8	0.309789	0.4990
9A	9B	1	7	0.541665	0.7629	9C	4	357	0.505989	0.2132
10A	10B	2	114	0.569955	0.5567	10C	1	1	0.630732	0.8055
11A	11B	3	1	0.469856	0.8136	11C	2	84	0.479072	0.6283
12A	12B	1	1	0.732799	0.8474	12C	2	81	0.661799	0.5658
13A	13B	1	1	0.796735	1.0	13C	2	197	0.574716	0.4963
14A	14B	1	9	0.601495	0.5360	14C	2	42	0.47512	0.4848
15A	15B	1	1	0.504967	0.6821	15C	2	78	0.432609	0.5832
16A	16B	2	163	0.45568	0.4780	16C	1	223	0.521828	0.3737
17A	17B	2	2	0.466728	0.6473	17C	1	141	0.478355	0.5291
18A	18B	5	2	0.399786	0.6372	18C	139	234	0.298924	0.4381
19A	19B	116	75	0.263188	0.4476	19C	181	277	0.235416	0.3726
20A	20B	1	1	0.530526	0.7027	20C	2	235	0.488823	0.4131
21A	21B	168	1	0.235401	0.8513	21C	1	33	0.418723	0.6247
22A	22B	157	1	0.31078	0.9321	22C	1	28	0.581979	0.6485

Object 1A – System A produced a perfect result as did system B. Both objects were correlated in the same relative positions.

Object 2A – System A correlated object 2B in the number one position as did system B. However system A correlated object 2C in the number two position whilst system correlated object 2C in position 44. This means that for the actual matching object 1C, 42 non-matching objects have been presented as being more similar.

Object 3A – System A correlated object 3B in the number one position as did system B. However system A correlated object 3C in the number two position whilst system B correlated object 3C in position 202 meaning for actual matching object 1C, 200 non-matching objects have been presented as being more similar.

Object 4A – System A correlated both objects in low positions on the correlation list, object 4B in position 34 and object 4C in position 45 meaning that system A has presented 33 objects as being more similar than the actual matching object 4B and 43 objects that are ranked as more similar that actual matching object 4C. System B also correlated both objects in low position but object 4C was correlated in a higher position (33) than object 4B (363) meaning that meaning that for System B object 4B has 361 non-matching objects ranked as more similar above it and object 4C has 32 non-matching objects ranked as more similar placed about it.

Object 5A – System A correlated object 5B in the top position and object 5C in position 10 meaning that for this object system A has suggested that 9 objects are more similar than the actual matching object. System B correlated the objects in the same relative order, (5B above 5C) but at different positions. 5B was correlated at position 13 whilst object 5C was correlated at position 217 meaning that object 5B, 12 non-matching objects have been considered to be more similar while for object 5C, 215 non-matching objects have been considered to be more similar.

Object 6A – System A has correlated object 6B in the top position and object 6C in position 95 meaning that system A has suggested that 93 objects are more similar than the actual matching object 6C. The result is the opposite for system B – object 6B has been correlated in position 47 meaning that 46 non-matching objects have been placed in a higher position than the actual matching object. System B has correlated object 6C in the top position.

Object 7A – System A has correlated object 7B in position two whilst object 7C has been correlated at position thirteen. This suggests that system A has correlated 11 objects as being more similar as the actual matching object 7C and has ranked a non-matching object in position one – higher than actual matching object 7B. System B however has correlated both objects in low positions and object 7C has been correlated at position 109, higher than object 7B which was correlated at position 268. This means that for object 7B, 266 non-matching objects have been ranked as being more similar than the actual matching object and for object 7C, 108 non-matching objects have been correlated as being more similar. Again this result demonstrates the differences between both systems even though they are both ranking objects based on the breech face impression. It is likely that system A managed the variance of the marks more successfully than system B.

Object 8A – System A has correlated object 8B at position 5 whilst object 8C has been correlated at position 31 meaning that 4 non matching objects have been correlated in higher positions that known matching object 8B and 29 non-matching objects have been correlated in higher positions that known matching object 8C. System B has produced an opposite result. Object 8B has been correlated at position 220 whilst object 8C has been correlated at position 8 meaning that for object 8B, 218 non-matching objects have been placed higher than the actual matching object and for object 8C, 7 non-matching objects have been placed higher than the actual matching object. This result is similar to those for objects 4A, 6A and 7A in that it adds evidence to support the idea that the markings alone are not the only determining factor in the performance of the systems.

Object 9A – System A has correlated object 9B at position one and object 9C at position four. This shows that system A has correlated 3 non-matching objects in higher positions that the actual matching object. System B has correlated object 9B at position seven and object 9C at position 357 meaning that for object 9B, 6 non-matching objects have been placed in a higher position than the actual matching objects whilst for object 9C, 355 non-matching objects have been placed in a higher position than the actual matching object.

Object 10A – Both systems have correlated object 10C at position one. Object 10B has been correlated at position two by system A whilst system has correlated object 10B at position 114 on the list meaning that for object 10B, 112 non-matching objects were correlated in a higher position than the actual matching object.

Object 11A – System A has correlated object 11B at position three and object 11C at position two. This result is unique thus far because it is the only occasion where the known matches have appeared at position 2 and 3 with a non-matching object in position 1. System B has correlated object 11B at position one whilst object 11C has been correlated at position 84 meaning that for this particular object, 82 non-matching objects were placed higher than the actual matching object. This result is of interest because there is disagreement between the systems in terms of relative ranking of the known matching objects. System A has placed object 11C (position 2) higher than object 11B (position 3). System B has produced a different result in that object 11C (position 84) was placed lower than object 11B (position 1).

Object 12A – Both system A and system B have correlated object 12B in the top position. System A has correlated object 12C in position 2 achieving a perfect result whilst system B has correlated object 12C in position 81 meaning that for this particular object, 79 non-matching objects were placed higher than the actual matching object.

Object 13A – Both system A and system B have correlated object 13B in position one. System A has correlated object 13C in position two achieving a perfect result whilst system B has correlated object

13C in position 197 meaning that 195 non-matching objects were correlated in a higher position than actual matching object 13C.

Object 14A – System A has achieved a perfect result correlating object 14B at position one and object 14C at position two. System B has correlated object 14B at position 9 and object 14C at position 42. For object 14B, 8 non-matching objects were correlated in a higher position than the actual matching object and for object 14C 40 non-matching objects were correlated in a higher position than the actual matching object.

Object 15A – System A has achieved a perfect result correlating object 15B at position one and object 15C at position two. System B has also correlated object 15B at position one but has correlated object 15C at position 78 meaning that for object 15C, 76 non-matching objects were correlated in a higher position than the actual matching object.

Object 16A – System A has achieved a perfect result correlating object 16C at position 1 and object 16B at position two. System B has correlated both objects in very low positions but has placed the objects in opposite order to system A. System B has correlated object 16C at position 223, lower than object 16B correlated at position 163. For object 16B, 162 non-matching objects were placed higher than the actual matching object and for object 16C, 221 non-matching objects were ranked higher than the actual matching object.

Object 17A – System A has achieved a perfect result correlating object 17C at position one whilst object 17B was correlated at position 2. System B has correlated the objects in opposite relative order. Object 17B was also correlated at position 2 but object 17C was correlated much lower on the correlation list at position 141.This means that a single non-matching object has been correlated above the actual matching object 17B and a key point is the similarity between the test object and the non-matching object placed in the number one position. For 17C, 139 non-matching objects have been correlated above the actual match.

Object 18A – System A has correlated object 18B at position 5 but correlation object 18C at position 139. This shows that system A has correlated four non-matching objects in positions higher than the actual matching object 18B and 137 non-matching objects ion higher positions than the actual matching object 18C. System B correlated object 18B at position two whilst object 18C was correlated at position 234. This means that for object 18B a single non-matching object was placed higher than the actual matching object. For object 18C, 233 non-matching objects were placed higher than the actual matching object.

Object 19A – System A has correlated object 19B at position 116 and object 19C at position 181. This means that system A has correlated 115 non-matching objects in a higher position that actual matching object 19B and 179 non-matching objects at a higher position than actual matching object 19C. System B has correlated object 19B at position 75 whilst object 19C was correlated at position 277 meaning that for object 19B, 74 non-matching objects were correlated above the actual match whilst for object 19C, 275 non-matching objects were placed above the actual matching object.

Object 20A – System A has achieved a perfect result correlating object 20B at position one and object 20C at position two. System B has also correlated object 20B at position one whilst object 20C has been correlated at position 235 meaning that 233 non-matching objects were placed higher than the actual matching objects.

Object 21A – System A has correlated object 21B at position 168 but has found object 21C in the number 1 position. 166 non-matching objects have ranked as more similar than the actual matching object. System B has correlated object 21B in the top position whilst object 21C was correlated in position 33. This means that for object 21C, 31 non-matching objects were placed higher than the actual matching object.

Object 22A –System A correlated object 22C in the top position and object 22B was found at position 157. This shows that system A has ranked 155 non-matching objects as being more similar than the actual matching object. System B correlated Object 22B in the top position whilst object 22C was correlated at position 28. This means that for object 22C, 26 non-matching objects were placed above the actual matching object.

A.3 – Results for Known Match Cartridge Cases (Firing Pin Algorithm)

This section presents an analysis of the firing pin algorithm results for systems A and B. Table A-3 presents the correlation list positions and the correlation scores for each system.

Table A-3: Results Comparison Matrix for System A and System B - Cartridge Cases (Firing Pin Algorithm)

	KNOWN MATCH 1					KNOWN MATCH 2				
Test Index	Known Match Object (1)	Sys A P KM1 FP	Sys B P KM1 FP	Sys A Corr Score KM1 FP	Sys B Corr Score KM1 FP	Known Match Object (2)	Sys A P KM2 FP	Sys B P KM2 FP	Sys A Corr Score KM2 FP	Sys B Corr Score KM2 FP
1A	1B	1	1	0.787411	0.643	1C	183	192	0.489746	0.184
2A	2B	3	1	0.549386	0.296	2C	57	166	0.509026	0.171
3A	3B	1	1	0.71997	0.542	3C	176	60	0.482933	0.256
4A	4B	9	4	0.510582	0.209	4C	1	1	0.686069	0.317
5A	5B	98	257	0.489731	0.113	5C	109	212	0.486473	0.12
6A	6B	1	1	0.617563	0.362	6C	6	2	0.546326	0.253
7A	7B	35	14	0.47229	0.136	7C	23	18	0.486313	0.129
8A	8B	74	1	0.496544	0.235	8C	3	48	0.5383	0.166
9A	9B	180	3	0.505035	0.284	9C	1	1	0.683223	0.455
10A	10B	49	13	0.50518	0.206	10C	1	1	0.679835	0.542
11A	11B	1	1	0.68996	0.498	11C	321	335	0.44638	0.098
12A	12B	1	1	0.66408	0.502	12C	315	345	0.438643	0.098
13A	13B	1	1	0.820897	0.774	13C	221	8	0.466964	0.247
14A	14B	1	1	0.810986	0.605	14C	287	359	0.448272	0.091
15A	15B	1	1	0.783375	0.538	15C	199	150	0.454856	0.141
16A	16B	1	1	0.645411	0.438	16C	2	2	0.596086	0.374
17A	17B	2	1	0.591348	0.294	17C	1	10	0.624086	0.192
18A	18B	1	8	0.668215	0.335	18C	2	11	0.626055	0.33
19A	19B	67	63	0.484314	0.156	19C	41	66	0.491379	0.154
20A	20B	1	1	0.771572	0.539	20C	2	2	0.634203	0.458
21A	21B	7	2	0.53994	0.386	21C	11	6	0.531968	0.319
22A	22B	12	32	0.521057	0.194	22C	82	176	0.483268	0.132

Object 1A – Both system A and system B have correlated object 1B in the top position. There is also an agreement of sorts between the systems because they both placed object 1C at low positions, System A at position 183 and system B at 192. This means that System A presented 181 non-matching objects as being more similar to actual matching object 1C. System B placed 190 non-matching objects above the actual matching object.

Object 2A – System A has correlated object 2B at position 3 and object 2C at position 57. This means that for the actual matching object 2B, two non-matches have been presented as more similar and for object 2C, 55 non-matching objects have been presented as more similar. System B has correlated object 2B at position one and object 2C at position 166 meaning that system B suggested 164 non-matching objects as being more similar than the actual matching object.

Object 3A – The result for object 3A is similar to that for object 2A. Both systems have correlated object 3B in position one. System A has placed object 3C at position 176. This shows that for object 3C, system A has suggested 174 non-matching objects as being more similar to the known match. System B has placed object 3C at position 60 meaning that system B suggested 58 non-matches as being more similar than the actual matching object.

Object 4A – Both systems have placed object 4C at position one. System A has placed object 4B at position 9 meaning that system A has placed 8 non-matches as being more similar than the known matching object. System B has placed object 4B at position 4 suggesting three non-matching objects as being more similar that actual matching object 4B.

Object 5A – Both systems have correlated both objects in low positions. System A has correlated object 5B in position 98 and object 5C in position 109. This result shows that system A has suggested that 97 non matching objects are more similar than the known matching object 5B and that 107 non-matching objects are more similar than known matching object 5C. System B has correlated the objects in opposite relative positions – object 5B was correlated at position 257 lower than object 5C which was correlated at position 212. This shows that for object 5C, system B suggested 211 non-matching objects as being more similar than the actual matching object whilst for object 5B, 255 matching objects were suggested as being more similar.

Object 6A – Both systems have correlated object 6B at position one on the correlation list. System A has correlated object 6C at position 6 meaning that system A has correlated 4 non-matching objects as being more similar than the actual matching object. System B has achieved a perfect result and has correlated object 6C at position two.

Object 7A – System A correlated object 7B at position 35 lower than object 7C which system A correlated at position 23. . This result shows that system A has correlated 33 non-matching objects above known match object 7B and 22 non-match objects above matching object 7B. System B ranked the objects in the opposite order placing object 7B highest at position 14 whilst object 7C was placed at position 18. For object 7B 13 non-matching objects have been ranked in higher positions and for object 7C, 16 non-matching objects have been suggested as being more similar.

Object 8A – System A correlated object 8B in position 74 and object 8C in position three. System A has therefore suggested that two non-matching objects are more similar than matching object 7C and 72 objects are more similar than object 8B. System B however, correlated the objects in opposite ranking order – object 8B was correlated in top position and object 8C was correlated in position 48. This means that system B suggested 46 non-matching objects as being more similar than actual matching object 8C.

Object 9A – Both system A and system B have correlated object 9C in the top position. System B has correlated object 9B in position three whilst system A has correlated object 9B in position 180. This shows that system has suggested 178 non-matching objects as being more similar than the actual matching object (9B) and system B has suggested that a single non-matching object is more similar than object 9B.

Object 10A – Both system A and system B have placed object 10C in the top position. System A has placed object 10B in position 49 and system B has placed object 10B in position 13. This shows that system A has correlated 47 non-matching objects in higher positions than actual matching object 10B and system B correlated 11 non-matching objects in higher positions than the actual matching object. Whilst there is agreement between the systems with regards to object 10C, system B has placed object 10B in a higher position than system A.

Object 11A - Both systems have correlated object 11B in position 1 and both systems have correlated object 11C in a very low position on the list. Object 11C appears at position 321 for system A and position 335 for system B. This means that that system A has suggested 319 non-matching objects that are more similar than the actual matching object and system B has suggested 333 non-matching objects as being more similar than matching object 11C.

Object 12A – This result is very similar to that obtained for object 11A in that the results for each system are not identical but they are very similar. Both systems have correlated object 12B in position one and both systems have correlated object 12C in a very low position on the list. Object 12C has been correlated at position 315 for system A and position 345 for system B. Therefore system A has suggested 313 non-matching objects that are more similar to the actual matching object and has suggested 343 non-matching objects as being more similar than matching object 12C.

Object 13A – Both systems have correlated object 13B at position one whilst system A has correlated object 13C at position 221 and system B has correlated object 13C at position 8. This shows that system A has suggested 219 non-matching objects that are more similar than the actual matching object whilst system B has suggested 6 non-matching objects as being more similar than the actual matching object.

Object 14A – Both systems have correlated object 14B in the top position and object 14C in much lower position on the correlation lists. System A correlated object 14C at position 287 meaning that system A has suggested 285 non-matching objects as being more similar than actual matching object 14A. System B has correlated object 14C at position 359 meaning that system B suggested 357 non-matching objects as being more similar than matching object 14C.

Object 15A –Object 15B has been correlated in the top position by both systems whilst the other object appears at a much lower position on the correlation lists. System A correlated object 15C at position 199 meaning system A has correlated 197 non-matching object as being more similar than the actual matching object. System B correlated the same object at position 150 meaning that system B suggested 148 non-matching objects as being more similar to the actual matching object 15C.

Object 16A – Both systems A and B achieved a perfect result and the objects are in the same relative positions.

Object 17A – System A has achieved a perfect result placing object 17C at position 1 and object 17B at position 2. System B has correlated a known match in position one but object 17B – opposite to system A. System B has placed object 17C at position 10. This still means that system B has correlated 8 non-matching objects as being more similar than the actual matching object.

Object 18A – System A has achieved a perfect result correlating object 18B at position 1 and object 18C at position 1. System B has correlated object 17B at position 8 and object 17C at position 11. Therefore system B suggested that 7 non-matching objects are more similar than actual matching object 18B and suggested that 9 non-matching objects are more similar than actual matching object 18C.

Object 19A – System A has correlated object 19B at position 67 and object 19C at position 41. System A has suggested that 40 non-matching objects are more similar than known matching object 19C and 65 non-matching objects are more similar than known matching object 19B. System B has produced the opposite result in terms of relative correlation list positions – object 19B was correlated at position 63 whilst object 19C was correlated at position 66. System B has therefore suggested that 62 non-matching objects were more similar than actual matching object 19B and has suggested that 64 non-matching objects were more similar than actual matching object 19C.

Object 20A – Both systems A and B achieved a perfect result and the objects are in the same relative positions.

Object 21A – System A has correlated object 21B at position 7 and object 21C at position 11. This means that for object 21B, system has suggested 6 non-matching objects as being more similar than the known match and for object 21C, 9 non-matches have been suggested as being more similar. System B has correlated object 21B at position 2 and object 21C at position 6. Therefore system B has correlated a non-matching object in the top position. For object 21C, 4 non-matching objects have been correlated higher positions that the actual matching object.

Object 22A - System A has placed object 22B at position 12 and object 22C at position 82. This means that system A has suggested 11 non-matching objects as being more similar that the actual matching object 22B and 80 non-matching objects as being more similar than object 22C. System has placed object 22B at position 32 and object 22C at position 176. System B has therefore suggested that 31 non-matches were more similar than object 22B and also suggested that 174 non-matching objects were more similar than actual matching object 22C

References

1. Agozino, B., Bowling, B., Ward, E., and St Bernard, G. (2009). 'Guns, crime and social order in the West Indies.' *Criminology and Criminal Justice*. 9 (3), pp. 287 – 305.

2. Ammenwerth E, Iller C, Mahler C (2006). 'IT-adoption and the interaction of task, technology and individuals: a fit framework and a case study.' *BMC Medical Informatics and Decision Making*. 6 (3).

3. Andres, A. R. and Hempstead, K. (2011). 'Gun control and suicide: The impact of state firearms regulations in the United States, 1995 – 2004.' *Health Policy*. 101 (1), pp. 95 – 103.

4. Argaman, U., Shoshani, E., and Hocherman, G. (2001). 'Utilisation of the IBIS in Israel'. *AFTE Journal*. (33) 3, pp. 269 – 272.

5. Banno, A. (2004). 'Estimation of bullet striation similarity using neural networks.' *Journal of Forensic Sciences*. 49 (3).

6. Barrett, M., Tajbakhsh, A. and Warren, G. (2011). 'Portable forensic ballistics examination Instrument: Advanced Ballistics Analysis System (ALIAS).' *AFTE Journal*. 43 (1), pp. 74 – 78.

7. BBC (2003). 'Balkan gun traffickers target UK.' [online] Available at: http://news.bbc.co.uk/1/hi/programmes/correspondent/3256318.stm [Accessed June 2011].

8. BBC (2007a). 'Britain's changing firearms laws' [online]. Available at: http://news.bbc.co.uk/1/hi/uk/7056245.stm [Accessed December 2010].

9. BBC (2008). 'Devastated by doctor's killing' [online]. Available at: http://news.bbc.co.uk/1/hi/wales/7529228.stm [Accessed December 2010].

10. BBC (2009).' In Pictures: Germany shootings' [online]. Available at: http://news.bbc.co.uk/1/hi/in_pictures/7937055.stm [Accessed July 2010].

11. BBC (2007b). 'PM's warning over gangs and guns' [online]. Available at: http://news.bbc.co.uk/1/hi/uk_politics/6386085.stm [Accessed July 2010].

12. BBC (2010a). 'Profile: Cumbria gunman Derrick Bird' [online]. Available at: http://www.bbc.co.uk/news/10216923 [Accessed December 2010].

13. BBC (2010b). 'Search for Raoul Moat intensifies amid public threat' [online]. Available at: http://www.bbc.co.uk/news/10565917.[Accessed July, 2010].

14. BBC (2010c). 'Shot PC David Rathband 'bears no malice' to Raoul Moat' [online]. Available at: http://www.bbc.co.uk/news/10583120 [Accessed December 2010].

15. Bean, P. (1999). 'Technology and Criminal Justice.' *International Review of Law, Computers and Technology*. 13 (3), pp. 365 – 371.

16. Bennett, T., and Holloway, K. (2004). 'Possession and use of illegal guns among offenders in England and Wales.' *The Howard Journal*. 43 (3), pp. 237 – 252.

17. Blunt L., Ohlsson, R., and Rosen, B.G. (1994). 'A comprehensive study of 3D surface topography measuring instruments.' In: *Proceedings of the 6th Nortrib Conference, Uppsala, Sweden*.

18. Blunt, L., Jiang, X., Leach, R., Harris, P., and Scott, P. (2008). 'The development of user-friendly software measurement standards for surface topography software assessment.' *Wear*. 264 (5-6), pp.389 – 393.

19. Blunt, L., and Jiang, X. (2003). 'Advanced techniques for the assessment of surface topography'. London: Butterworth-Heinemann.

20. Braga, A.A., Kennedy, D.M., Piehl, A.M and Waring, E.J. (2001). 'Reducing gun violence. The Boston gun project's Operation Ceasefire. Part two: Measuring the impact of Operation Ceasefire.' *U.S Department of Justice Research Report*. National Institute of Justice.

21. Braga, A.A., and Pierce, G.L. (2004). Linking crime guns: The impact of ballistics analysis technology on the productivity of the Boston Police Department's ballistics unit. *Journal of Forensic Sciences.* 49 (4).

22. Brinck, T. (2008). 'Comparing the performance of IBIS and BulletTRAX -3D technology using bullets fired through 10 consecutively rifled barrels.' *Journal of Forensic Science*. 53 (3), pp. 677 – 682.

23. Bullock, K. And Tilley, N. (2002). 'Shootings, gangs and violent incidents in Manchester: Developing a crime reduction strategy.' *Home Office Crime Reduction Research Series Paper 13.*Home Office.

24. Bullock, K. and Tilley, N. (2008). 'Understanding and tackling gang violence.' *Crime Prevention and Community Safety*. 10 (1), pp. 36 – 47.

25. Bullock, K. and Tilley, N. (2009). 'Evidence-based policing and crime reduction.' *Policing. A Journal of Policy and Practice*. 3 (4), pp. 381 – 387.

26. Bunch, S.G. (2000). 'Consecutive matching striation criteria: A general critique.' *Journal of Forensic Science.* 45 (5), pp. 955 – 962.

27. Bureau of Alcohol Tobacco and Firearms. (2000). 'Commerce in Firearms in the United States.' *Washington DC: Bureau of Alcohol, Tobacco and Firearms*.

28. Burns, D.C. (2001). 'When used in the criminal legal process forensic science shows a bias in favour of the prosecution. Discuss.' *Science and Justice*. 41 (4), pp. 271 – 277.

29. Calvin, C.A., and Goh, A. (2005). 'Validation of the technology acceptance model for police'. *Journal of Criminal Justice*. 33 (1), pp. 89 – 95.

30. Campbell, L. (2010). 'Responding to gun crime in Ireland.' *British Journal of Criminology.* 50 (3), pp. 414-434.

31. Chan, R. (2000). ‘The relationship between acquisition positions of cartridge cases and discrepancy in correlation scores on IBIS.’ *AFTE Journal*. 32 (4), pp. 337 – 341.

32. Chayko, G.M. and Gulliver, E.D. (1999). ‘Forensic Evidence in Canada’. Canada Law Book Inc.

33. Chu, W., Song, J., Vorburger, T., and Ballou, S. (2010). ‘Striation density for predicting the identifiability of fired bullets with automated inspection systems.’ *Journal of Forensic Sciences.* 55 (5), pp. 1222 – 1226.

34. Chumbley, L.S., Morris, M.D., Kreiser, M.J., Fisher, C., Craft, J., Genalo, L.J., Davis, S., Faden, D. and Kidd, J. (2010). ‘Validation of tool mark comparisons obtained using a quantitative, comparative statistical algorithm.’ *Journal of Forensic Sciences*. 55 (4), pp. 953 – 961.

35. Cloward, R. and Ohlin, L. (1960). ‘Delinquency and opportunity’. NY: Free Press.

36. Cohen, A.K. (1955). ‘Delinquent boys: The culture of the gang.’ Glencoe IL.

37. Cork, D.L., Rolph, J.E., Meieran, E.S., and Petrie, C.V. (2008). ‘Ballistics Imaging: Committee to assess the feasibility, accuracy and technical capability of a national ballistics database.’ *National Research Council.*

38. Crewdson, K., Lockley, D, Weaver, A., and Davies, G.E Davies. (2009). ‘Is the prevalence of deliberate penetrating trauma increasing in London? Experiences of an urban pre-hospital trauma service.’ *Injury*. 40 (5), pp. 560-563.

39. Criminal Justice Act 1967.

40. Cullen. (1996). ‘The public inquiry into the Shootings at Dunblane Primary School on 13 March 1996.’ *London: The Stationary Office.*

41. Cutts, A., Bridle, A and Bleetman, A. (2006). ‘Gun culture – recent trends in epidemiology and management in the UK.’ *Journal of Orthopaedic Nursing*. 10 (2), pp. 113 – 116.

42. Daubert v. Merrell Dow Pharmaceuticals, Inc. (1993) 509 U.S. 579, 589.

43. Dauvergne, M. and L. de Socio (2008) ‘Firearms and violent crime.’ *Juristat.* 28(2). Cat. No. 85–002. Ottawa: Canadian Centre for Justice Statistics, Canada.

44. De Kinder, J. (2002a). ‘Ballistics fingerprinting databases’. *Science and Justice*. 42 (4), pp. 197 -203.

45. De Kinder, J. (2002b). ‘Review AB1717 report. Technical Evaluation: Feasibility of a ballistics imaging database for all new handgun sales. Independent Review for California Department of Justice.’ *California Department of Justice.*

46. De Kinder, J., Tulleners, F., and Thiebaut, H. (2004). ‘Referencing ballistic imaging database performance.’ *Forensic Science International*. 140 (2-3), pp. 207 – 215.

47. Decker, S.H., and Curry, D. G. (2002). ‘Gangs, gang homicides, and gang loyalty: Organised crimes or disorganised criminals.’ *Journal of Criminal Justice*. 30 (4), pp. 342 – 352.

48. Edwards, H.T., Gatsonis, C., and Kafadar, K. (2009). 'Strengthening forensic science in the United States: A path forward.' *Washington DC: The National Academies*.

49. Evofinder (2011). Evofinder History [online]. Available at: http://www.biscondor.com/hist.htm [Accessed July 2011].

50. Farrell, G., Tilley, N., Tseloni, A. and Mailley, J. (2010). 'Explaining and sustaining the crime drop: Clarifying the role of opportunity-related theories.' *Crime Prevention and community Safety.* 12 (1), pp. 24.41.

51. Farrington, D.P., Gill, M., Waples, S.L. and Argomaniz, J. (2007). 'The effects of closed-circuit television on crime: meta-analysis of an English national quasi-experimental multi-site evaluation.' *Journal of Experimental Criminology*. 3 (1), pp. 21 – 38.

52. Fay, S.J. (1998). 'Tough on crime, tough on civil liberties: Some negative aspects of the wholesale adoption of CCTV surveillance during the 1990s.' *International Review of Law, Computers and Technology.* 12 (2), pp. 315 – 347.

53. Firearms Act 1920.

54. Firearms Act 1937.

55. Firearms Act 1968.

56. Firearms (Amendment) Act 1988.

57. Firearms (Amendment) (No 2) Act 1997.

58. Field, B.F., Kelley, E.F., and McCabr, R.M. (1996). 'Specification for interoperability between ballistics imaging systems. Part 1 – cartridge cases.' *National Institute of Standards and Technology.*

59. Foreman, L.A., and Evett, I.W. (2001). 'Statistical analyses to support forensic interpretation for a new ten-locus STR profiling system.' *International Journal of Legal Medicine*. 114 (3), pp. 147-155.

60. Gao, F., Leach, R.K., Petzing, J. and Coupland, J.M. (2008). 'Surface measurement errors using commercial scanning white light interferometers.' *Measurement Science and Technology*. 19 (1).

61. George, W. (2004a). 'A validation of the Brasscatcher portion of the NIBIM/IBIS system.' *AFTE Journal.* 36 (4), pp. 286 – 288.

62. George, W (2004b). 'The validation of the Brasscatcher portion of the NIBIN/IBIS system part two: "Fingerprinting Firearms" reality or fantasy.' *AFTE Journal*. 36 (4), pp.289 – 296.

63. Geradts, Z., Keijzer, J., and Keereweer, I. (1994). 'A new approach to automatic comparison of striation marks.' *Journal of Forensic Sciences*. 39(4), pp. 974 – 980.

64. Gill, M., Rose, A., and Collins, K. (2005). 'A good practise guide for the implementation of redeployable CCTV (Online Report 16/05).' *London: Home Office.*

65. Gill, M., and Spriggs, A. (2005). ‘Assessing the Impact of CCTV (Research Study No. 292).’ *London: Home Office*

66. Gill, P. (2002). ‘Role of short tandem repeat DNA in forensic casework in the UK – past, present and future perspectives.’ *Biotechniques.* 32 (2), pp. 366-385.

67. Giverts, P. (2004). ‘Using the IBIS for the examination of bullets fired from polygonally barrelled guns such as the Glock pistol.’ *AFTE Journal.* 36(3), pp. 226 – 229.

68. Gonzales, A.R., Henke, T.A., Hart, S.V. (2005).’ Reducing Gun Violence. Operation Ceasefire in Los Angeles. U.S Department of Justice Research Report.*’ National Institute of Justice.*

69. Guardian (1987) ‘Gunman in combat gear kills himself after 14 die in shooting spree’ [online]. Available at: http://www.guardian.co.uk/fromthearchive/story/0,12269,1286273,00.html [Accessed on 6th December 2010].

70. Guardian (1996) ‘Dunblane Massacre’ [online]. Available at: http://century.guardian.co.uk/1990-1999/Story/0,,112749,00.html [Accessed on 6th December 2010].

71. Guardian (2007). ‘Two jailed for smuggling handguns from eastern Europe’ [online]. Available at: http://www.guardian.co.uk/uk/2007/feb/17/ukguns.news1 [Accessed June 2011].

72. Guardian (2010) ‘Birmingham stops Muslim CCTV surveillance scheme’ [online]. Available at: http://www.guardian.co.uk/uk/2010/jun/17/birmingham-stops-muslim-surveillance-scheme [Accessed December 2010].

73. Hales, G., Lewis, C. And Silverstone, D. (2006).’ Gun Crime: the market in and the use of illegal firearms. Home Office Research Study 298.’ *Home Office.*

74. Hallsworth, S., and Silverstone, D. (2010). ‘“That’s life innit” A British perspective on guns, crime and social order.’ *Criminology and Criminal Justice.* 9 (3), pp. 359 – 377.

75. Hannam, A.G. (2010). ‘Trends in converted firearms in England and Wales as identified by the National Firearms Forensic Intelligence Database (NFFID) between September 2003 and September 2008.’ *Journal of Forensic Sciences*. 55 (3), pp. 757 – 766.

76. Hayden, C., Hales, G., Lewis, C., and Silverstone, D. (2008) ‘Young people convicted of firearms offences in England and Wales: an exploration of family and educational background as opportunities for prevention.’ *Policy Studies*. 29 (2), pp. 163 – 178.

77. Heard, B.J (2008). ‘Handbook of firearms and ballistics. Examining and interpreting forensic evidence.’ *Wiley-Blackwell*.

78. Henderson, C. (2004). ‘Driving crime down, denying criminals the use of the road [Automatic Number Plate Recognition (ANPR)].’ *Police Standards Unit, PA Consulting Group. The Stationary Office.*

79. Hemenway, D., and Richardson, E. (1997). 'Characteristics of automatic or semi-automatic firearm ownership in the United States.' *American Journal of Public Health*. 87 (2), pp. 286 – 288.

80. Hepburn, L.M., and Hemenway, D. (2004). 'Firearm availability and homicide: A review of the literature.' *Aggression and Violent Behaviour*. 9 (4), pp. 417 – 440.

81. INTERPOL (2010). 'INTERPOL Firearms Tracing System' [online]. Available at: http://www.interpol.int/public/weapons/default.asp [Accessed December 2010].

82. Karger, B., Billeb, E and Koops, E. (2002) 'Accidental firearm fatalities. Forensic and preventative implications.' International Journal of Legal Medicine. 116 (6), pp. 350 – 353.

83. Karlsson, T., Isaksson, B., and Ormstad, K. (1993). 'Gunshot fatalities in Stockholm, Sweden with special reference to the use of illegal weapons.' *Journal of Forensic Sciences*. 38 (6), pp. 1409 -1421.

84. Kaasa, S.O., Peterson, T., Morris, E.K., and Thompson, W.C. (2007). 'Statistical inference and forensic evidence: Evaluating a bullet lead match.' *Law and Human Behaviour*. 31 (5), pp. 433 – 447.

85. Kellerman, A.L, Rivara, F.P, Rushforth, N.B., Banton, J.G., Reay, D.T., Francisco, J.T., Locci, A.B., Prodzinski, J., Hackman, B.B., and Somes, G. (1993). 'Gun ownership as a risk factor for homicide in the home.' *The New England Journal of Medicine*. 329 (15), pp. 1084 – 1091.

86. Kennedy, D.M., Braga, A.A., and Piehl, A.M. (2001). 'Reducing gun violence. The Boston gun project's Operation Ceasefire. Part one: Developing and implementing Operation Ceasefire. U.S Department of Justice Research Report.' *National Institute of Justice.*

87. Kerstholt, J., Eikelboom, A., Dijkman, T., Stoel, R., Hermse, R., van Leuven, B. (2010). 'Does suggestive information cause a confirmation bias in bullet comparisons?' *Forensic Science International.* 198 (1-3), pp. 138 – 142.

88. Koffman, A. and Silverwater, H. (2001). 'IBIS correlation results – Analysing methodology and reliability factor.' *AFTE Journal*. 33(4), 342 – 352.

89. Kopel, D, B. And Burnett, H.S. (2003). 'Ballistic Imaging: Not ready for prime time.' *Policybackgrounder, National Center for Policy Analysis*. 160.

90. Koper, C.S. (2005). 'Purchase of multiple firearms as a risk factor for criminal gun use: Implications for gun policy and enforcement.' *Criminology and Public Policy.* 4 (4), pp. 749 – 778.

91. Krug. E.G., Powell, K.E. and Dahlberg, L.L. (1998). 'Firearm related deaths in the United States and 35 other high and upper middle income countries.' *International Journal of Epidemiology.* 27 (2), pp. 214-221.

92. Laboratory Imaging s.r.o (2011) [online]. Available at: http://www.forensic.cz/en/products/balscan [Accessed August 2011].

93. Lepik, D. and Poldsam, U. (2007) 'Gunshot injuries in Estonia 2002 – 2004.' *Forensic Science International*. 169 (supplement), pp. S36 – S40.

94. Levitt, T. (1986). 'The Marketing Imagination.' *Simon & Schuster.*

95. Lockyer, B. (2003). 'Feasibility of a California Ballistics Identification System. Assembly Bill 1717.' *California Department of Justice*.

96. Manchester Evening News (2010) 'Pair charged with firearms and drug offences' [online]. Available at: http://menmedia.co.uk/manchestereveningnews/news/crime/s/1371641_pair_charged_with_firearms_and_drug_offences. [Accessed December 2010].

97. Marshall, B., Webb, B., and Tilley, N. (2005). 'Rationalisation of current research on guns, gangs and other weapons: Phase 1.' *Jill Dando Institute of Crime Science*. University College London.

98. McKeganey, N. and Norrie, J. (2000). 'Association between illegal drugs and weapon carrying in young people in Scotland: schools' survey.' British Medical Journal. Vol 320 (7240), pp. 982 – 984.

99. Merton, R. K. (1938) 'Social, structure and anomie.' *American Sociological Review.* 2, pp. 672 – 682.

100. Metropolitan Police (2010). 'Specialist Crime – Trident' [online]. Available at: http://www.met.police.uk/scd/specialist_units/trident_trafalgar.htm [Accessed December 2010].

101. Moore, G. (1999). 'Crossing the Chasm: Marketing and selling technology products to mainstream customers.' *HarperBusiness.*

102. Morris, K. (2009). 'UK doctors begin reporting gun and knife crime.' *The Lancet.* 374 (9707), pp. 2041 – 2042.

103. Morris, M.G., and Dillon, A.P. (1996). 'The importance of usability in the establishment of organisational software standards for end user computing.' *International Journal of Human – Computer Studies*. 45 (2), pp. 243 – 258.

104. NABIS (2011). 'Intelligence Cell' [online]. Available at: http://www.nabis.police.uk/intellcell.asp [Accessed July 2011].

105. Nennstiel, R., and Rahm, J. (2006a). 'A parameter study regarding the IBIS correlator.' *Journal of Forensic Sciences*. 51 (1), pp. 18-23.

106. Nennstiel, R., and Rahm J. (2006b). 'An experience report regarding the performance of the IBIS correlator. *Journal of Forensic Sciences*. 51 (1), pp. 24-30.

107. Nichols, R.G. (1997). 'Firearm and toolmark identification criteria: A review of the literature.' *Journal of Forensic Sciences*. 42(3), pp. 466 – 474.

108. Nichols, R.G. (2003). 'Firearm and toolmark identification criteria: A review of the literature Part 2.' *Journal of Forensic Sciences*. 48 (2).

109. Nichols, R.G. (2007). 'Defending the scientific foundations of the firearms and tool mark identification discipline: Responding to recent challenges.' *Journal of Forensic Sciences.* 52 (3), pp. 586 – 594.

110. Niederkrotenthaler, T., Benedikt, T., Herberth, A., Kapusta, N.D, Voracek, M., Dervic, K., Etzerdorfer, E., and Sonneck, G. (2009). 'Can media effects counteract legislation reforms? The case of adolescent firearm suicides in the wake of the Austrian firearm legislation.' *Journal of Adolescent Health*. 44 (1), pp. 90 – 93.

111. Nor Azura, G., Choong-Yeun, L., and Abdul Aziz, J. (2010). 'Analysis of geometric moments as features for firearm identification.' *Forensic Science International*. 198 (1-3), pp. 143 – 149.

112. Nottingham Post (2010) 'Gun crime in city down by 43% compared to last year' [online]. Available at: http://www.thisisnottingham.co.uk/news/Gun-crime-city-43-compared-year/article-2965412-detail/article.html [Accessed December 2010].

113. Norris, C., and McCahill, M. (2006). 'CCTV: Beyond penal modernism?' *British Journal of Criminology*. 46 (1), pp. 97 – 118.

114. Nutley, S., Davies, H.T.O. and Tilley, N. (2000). 'Viewpoints: Editorial. Getting research into practice.' *Public Money and Management*. 20 (4), pp. 3-6.

115. Ozanne-Smith, J., Ashby, K., Newstead, S., Stathakis, V.Z., and Clapperton, A. (2004). 'Firearm related deaths: the impact of regulatory reform.' *Injury Prevention*. Vol 10 (5), pp. 280 -286.

116. Papillon Systems (2008). 'Arsenal ABIS User References' [online]. Available at: http://www.papillon.ru/files/image/content/2008/pic/Arsenal/Arsenal_Reference_list_v_1_2.pdf [Accessed July 2011].

117. Parliament UK (2010). 'Home Affairs Committee announces a new inquiry into Firearms Control' [online]. Available at: http://www.parliament.uk/business/committees/committees-a-z/commons-select/home-affairs-committee/news/firearms-control/ [Accessed December 2010].

118. Persad, I.J, Srinvas Reddy, R., Saunders, M.A and Patel, J. (2005). 'Gunshot injuries to the extremities: experience of a UK trauma centre.' *Injury.* 36 (3), pp. 407 – 411.

119. Pistols Act 1903.

120. Press Association (2010) 'Gardens searched for drugs and guns' [online]. Available at: http://www.google.com/hostednews/ukpress/article/ALeqM5j2FX32bjVRc8ZvSNH5n_izMITuzg?docId=N0123391290000572403A [Accessed December 2010].

121. Risinger, M.D., Saks, M.J., Thompson, W.C. and Rosenthal, R. (2002). 'The Daubert / Kumho implications of observer effects in forensic science: Hidden problems of expectation and suggestion.' *California Law Review*. 90 (1), pp. 3 – 56.

122. Roberge, D., and Beauchamp, A. (2006). 'The use of BulletTRAX-3D in a study of consecutively manufactured barrels.' *AFTE Journal*. 38 (2), pp. 166 – 172.

123. Roberts, C.H, and Innes, M. (2009). 'The "death" of Dixon? Policing gun crime and the end of the generalist police constable in England and Wales.' *Criminology and Criminal Justice.* 9 (3), pp. 337 – 357.

124. Saks, M.J. (2010). 'Forensic identification: From a faith-based "Science" to a scientific science.' *Forensic Science International*. 201 (1-3), pp. 14-17.

125. Sarma, K., Griffin, D., and Kola, S. (2010). Firearm-assisted suicide: Legislative, policing and clinical concerns. *Journal of Forensic and Legal Medicine*. 17 (1), pp. 33 – 37.

126. SBC Company (2011). 'About the Company' [online] Available at: http://sbc-spb.com/index.php?option=com_content&view=section&layout=blog&id=5&Itemid=5&lang=en [Accessed August 2011].

127. Shaw, C.R and McKay, H.D. (1931). 'Social factors in juvenile delinquency.' *Washington DC: Government Printing Office.*

128. Schwarz, A. (2004). 'A challenge to the admissibility of firearms and toolmark identification: Amicus brief prepared on behalf of the defendant in United States Vs Kain, Crim. No. 03-573-1 (E.D. PA. 2004).' *The Journal of Philosophy, Science and Law*. Vol 4.

129. Schwarz, (2007). 'Commentary on Nichols, R.G. (2007). Defending the scientific foundations of the firearms and tool mark identification discipline: Responding to recent challenges.' *Journal of Forensic Sciences*. 52 (6), pp. 1414 – 1415.

130. Shaw, M., Tunstall, H., and Dorling, D. (2005). 'Increasing inequalities in risk of murder in Britain: trends in the demographic and spatial distribution of murder, 1981 – 2000'. *Health and Place*. 11 (1), pp. 45 – 54.

131. Sheptycki, J. (2009). 'Guns, crime and social order: A Canadian perspective.' *Criminology and Criminal Justice*. 9 (3), pp. 307 – 336.

132. Sherman, L.W. (2001). 'Reducing gun violence: What works, what doesn't, what's promising.' *Criminology and Criminal Justice*. 1(1), pp. 11 – 25.

133. Silverwater, H., and Koffman, A. (2000). 'IBIS correlation results – Improvements.' *AFTE Journal*. 32 (1), pp. 32 – 39.

134. Smith, J. (2003). 'The nature of personal robbery. Home Office Research Study 254.' *Home Office.*

135. Smith, K., Flatley, J., Coleman, K., Osbourne, S., Kaiza, P and Roe, S. (2010) 'Homicides, firearms offices and intimate violence 2008/09. Supplementary volume 2 to crime in England and Wales 2008/09. Home Office Statistical Bulletin.' *Home Office.*

136. Smith, O. C., Jantz, L., Berryman, H. E., and Symes, S. A. (1993) 'Effects of human decomposition on bullet striations.' *Journal of Forensic Sciences*. 38(3), pp. 593-598.

137. Song, J., Vorburger, T., Ballou, S., Ma, L., Renegar, T., Zheng, A., and Ols, M. (2009). 'Traceability for ballistics signature measurements in forensic science.' *Measurement*. 42 (9), pp. 1433 – 1438.

138. Song, J., Vorburger, T., Thompson, R., Renegar, T., Zheng, A., Ma, L., Yen. J. and Ols, M. (2010). 'Three steps towards metrological traceability for ballistics signature measurements.' *Measurement Science Review*. 10 (1), pp. 19 – 21.

139. Sorenson, S.B., and Berk, R.A. (1999). 'Young guns: an empirical study of persons who used a firearm in a suicide or a homicide.' *Injury Prevention.* 5 (4), pp. 280 – 283.

140. Spapens, T. (2007). 'Trafficking in illicit firearms for criminal purposes within the European Union.' *European Journal of Crime, Criminal Law and Criminal Justice.* 15 (3), pp. 359 – 381.

141. Spitzer, R.J. (1998). 'The politics of gun control.' *Chatham House Publishers.*

142. Squires, P. (2008). '"Gun Crime". A Review of evidence and policy'. *Centre for Crime and Justice Studies*. Kings College London.

143. Stout, K.J. and Blunt, L. (2000). 'Three-dimensional surface topography. 2nd Edition.' *Prenton-Press.*

144. Sutherland, E.H, Cressey, D. R and Luckenbill, D.F. (1992). 'Principles of criminology, eleventh edition.' *Rowman and Littlefield*.

145. Tilley, N. (2010). 'Whither problem-oriented policing.' *Criminology and Public Policy.* 9 (1), pp. 183 – 195.

146. Thomas, T.R., Rosen, B.G., Zahouani, H., Blunt, L., Mansori, M. El. (2011). 'Traceology, quantifying finishing machining and function: A tool and wear mark characterisation study.' *Wear*. 271 (3-4), pp. 553 – 558.

147. Thrasher, F. (1927). 'The gang. A study of 1313 gangs in Chicago.' *Chicago: University of Chicago Press*.

148. Tulleners, F.A. (2001). 'Technical Evaluation: Feasibility of a ballistics imaging database for all new handgun sales. Evaluation for California Department of Justice.' *California Department of Justice.*

149. Vaughan, R.D, Carthy, J.F, Armstrong, B., Walter, H.J, Waterman, P.D and Tiezzi, L. (1996). 'Carrying and using weapons: A survey of minority junior high school students in New York City.' *American Journal of Public Health*. 86(4), pp. 568 – 572.

150. US News (2003) 'Do bullets tell tales?' [online]. Available at: http://www.usnews.com/usnews/culture/articles/031124/24forensic.htm. [Accessed December 2010].

151. Verzeletti, A., Astorri, A., De Ferrari, F. (2009) ‘Firearm-related deaths in Brescia (Northern Italy) between 1994 and 2006. A retrospective study.’ *Journal of Forensic and Legal Medicine.* 16 (6), pp. 325 – 331.

152. Violent Crime Reduction Act 2006.

153. Waples, S., and Gill, M. (2006). ‘The effectiveness of redeployable CCTV.’ *Crime Prevention and Community Safety*. 8 (1), pp. 1 -16.

154. Waples, S., Gill, M., and Fisher, P. (2009). ‘Does CCTV displace crime?’ *Criminology and Criminal Justice.* 9 (2), pp. 207 – 224.

155. Warlow, T.A. (2007). ‘The criminal use of improvised and re-activated firearms in Great Britain and Northern Ireland’. *Science and Justice*. 47 (3), pp. 111-119.

156. Welsh, B.C., and Farrington, D.P. (2009). ‘Public area CCTV and crime prevention: An updated systematic review and meta-analysis.’ *Justice Quarterly*. 26(4), pp. 716 – 745.

157. Wheal, H., and Tilley, N. (2009).’ Imitation gun law: an assessment.’ *The Howard Journal.* 48 (2), pp. 172 – 183.

158. Wintemute, G.J., Romero, M.P., Wright, M.A. and Grassel, K.M. (2004). ‘The life cycle of crime guns: A description based on guns recovered from young people in California.’ *Annals of Emergency Medicine*. 43 (6), pp. 733-742.

159. Woellert, L (2002). ‘Ballistics fingerprinting: A lifesaver’ [online]. Available at: http://www.businessweek.com/bwdaily/dnflash/oct2002/nf20021024_3210.htm [Accessed August 2011].

160. Wood, J and Alleyene, E. (2010). ‘Street gang theory and research: Where are we now and where do we go from here?’ *Aggression and Violent Behaviour*. 15 (2), pp. 100 – 111.

161. Yilmaz, R, Birincioglu, I., Bulent Uner, H., Erkol, Z., Butun, C., Acikgoz, D. And Bulut, E.R. (2009). ‘Handmade guns in Trabzon, Turkey’. *Journal of Forensic Sciences*. 54 (4), pp. 881 – 883.

162. Xie, F., Xiao, S., Blunt, L., Zeng, W., and Jiang, X. (2009). ‘Automated bullet identification system based on surface topography techniques.’ *Wear.* 266 (5-6), pp. 518 – 522.