The effectiveness of the UK national DNA database

Aaron Opoku Amankwaa, Carole McCartney[*]

Science and Justice Research Interest Group, School of Law, Northumbria University, Newcastle Upon Tyne, NE1 8ST, UK

ARTICLE INFO

ABSTRACT

Since the emergence of forensic DNA profiling and the corollary creation of DNA databases, efforts to maximise the efficiency and utility of DNA technology have intensified. Such efforts are expedient given the imperative that expenditure on DNA should be cost-effective and the benefits demonstrable. The practice of retaining DNA profiles in databases, either obtained from individuals involved in criminal investigations, or retrieved from suspected crime scenes, has spread globally. The UK's National DNA Database (NDNAD), created in 1995, is both one of the longest established, and biggest of such forensic DNA databases internationally. As such, it is instructive to look at whether there is evidence to demonstrate the effectiveness of this DNA database. This paper thus examines efforts to gauge the effectiveness of forensic DNA databases, concluding that while the UK NDNAD may have led directly to convictions in high profile crimes, its broader impact upon public security goals remains elusive.

1. Introduction

Thanks to television detectives and their ilk, the public are by now familiar with criminals leaving their DNA at the scene of a crime — allowing the police to quickly identify perpetrators, as well as linking them to any other crimes they may have committed. Even if there is no arrest before the end credits, DNA profiles derived from samples retrieved from crime scenes can be stored in a database, and later used to find a 'matching' suspect. In real life, this practice of storing DNA retrieved from crime scenes in a database has led directly to convictions in high profile crimes, such as that of the 1984 rape and murder of Melanie Road [1,2].[1] The utility of DNA in such serious crimes has helped secure significant financial investment and political commitment to expand forensic DNA databases. Yet, while the value of a DNA database in individual (particularly unsolved) cases is easy to find, (most often in media reports), the aggregate value of a DNA database remains unascertained.

In fact, it might be presumed from the prevalence of acclaim in the media, and the significance attached to a DNA 'match' by criminal justice agents, that DNA databases make a vital contribution to criminal justice aims. In just one recent example from Australia, the Police Minister stated that: 'We know DNA is a more effective way for police to prosecute and solve crime', arguing that expanding DNA databases will 'help bring down high harm and high volume crimes… - helping police solve thousands of unsolved crimes and helping to catch serious offenders more easily' [3]. Such claims prompt the question of how it is known that DNA is 'more effective', as the authority, reliability and relevance of claims made for DNA databases as a policing tool are unclear, and 'the significance of what can be gleaned from such data, particularly the limitations, is not widely understood' [4]. Indeed, in 2010, the US Urban Institute undertook an examination of the benefits of DNA collection, as increasing numbers of States enacted laws to authorise the collection of DNA upon arrest, and yet, 'despite their widespread adoption, little is known about the investigative utility of collecting DNA from arrestees (…)' [5].[2]

The primary purpose of a forensic DNA database is to provide the police with intelligence on who may have been present at the scene of a crime, particularly where the identity of the participant(s) is unknown [7]. A database of DNA profiles from crime scenes may also provide intelligence on the existence of 'links'

---

* Corresponding author.

E-mail addresses: aaron.amankwaa@northumbria.ac.uk (A.O. Amankwaa), carole.mccartney@northumbria.ac.uk (C. McCartney).

[1] Advances in DNA technology in the 1990s resulted in the generation of a DNA profile from a stored semen sample from the crime scene, which was loaded on the UK's National DNA Database (NDNAD). There were no matches until 2014, when Christopher Hampton's daughter was arrested, and her DNA profile loaded onto the NDNAD, which was a close match with the DNA from the 1984 murder. Police then took a DNA sample from her father and his DNA profile matched the crime scene sample, leading to his conviction and a life sentence.

[2] Their research concluded that 'arrestee DNA laws increased hits to forensic profiles, but to an unknown degree [as] most states did not collect the data necessary to calculate the discrete impact of arrestee profiles on public safety' [6].

between different crime scenes, potentially identifying serial offenders and aiding in the analysis of crime patterns [8,9]. To determine how well the UK DNA database assists in the performance of these tasks, a measure must be made of the 'effectiveness' of the database; gauging the level at which the actual outcomes of the system meet expectations [10]. Another closely related indicator is efficiency, which is a measure of the value or worth of a system by comparing its actual outcomes to that of alternative systems or a cost/input-benefit analysis of a system [11,12]. In the context of forensic DNA databasing and criminal investigation, an *effective* database should contain both subject reference profiles and crime scene profiles and generate relevant matches that contribute to the prevention, detection, and prosecution of crime — i.e. make a net contribution to public security. An *efficient* forensic DNA database system should result in better public security outcomes from use of the DNA database than alternative systems, or at the very least, its public security outcomes should merit the input required, (the 'costs') of the operation of the DNA database.

This paper aims then to assess the effectiveness of the UK National DNA Database in assisting with the prevention and detection of crime, and the prosecution and conviction of criminals. There are of course additional considerations, which may require that conclusions are moderated, as any assessment necessarily takes place against a backdrop of debate over the most appropriate legal regime to govern the NDNAD, which will include the acceptability and ethical operation of the database [13—15]. The 'balancing' of private and public interests is necessary, with the inclusion of individuals (and the duration of their inclusion) on databases (and therefore the diminishment of their right to privacy) needing to be 'proportionate' with the aims of law enforcement [16—18]. Thus, the 'cost' to society and individuals when infringing their rights, must be balanced with the benefit to society of increased public security. However, establishing this balance is difficult with a lack of adequate evidence to demonstrate how DNA databasing actually contributes to public security.

After briefly outlining the creation of the UK NDNAD and subsequent debate over its form and function, we examine the criteria by which to measure the effectiveness of DNA databases, what is currently measured, and the advantages and limitations of differing models used for measuring effectiveness. The paper concludes by questioning the efficiency of the UK NDNAD, given the lack of meaningful evidence for its effectiveness.

2. The creation of the UK NDNAD

The UK was the first country to embark upon the so-called forensic DNA 'revolution' [19,20], with DNA profiling first applied to an immigration dispute in 1988 [21,22].[3] It was soon realised that this technique had potentially far wider application within the criminal justice system. And so it proved, with the use of DNA in policing expanding, assisted by rapid scientific and technological developments accompanied by incremental legal reforms, enabling the taking and use of DNA profiles to become integral to the criminal process. The enthusiastic adoption of the new technique was fuelled by both political and media hyperbole about the benefits of DNA profiling to crime detection and reduction. DNA profiling was hailed as an uncomplicated success story, with the NDNAD established without any dedicated legislation, thus evading any focussed political or public debate [7]. The database was supported by a highly permissive legal regime, the result of continual tinkering with the law between 1995 and 2003 governing: from

whom a sample could be taken and when in the criminal process; the authority required to sanction and perform sampling; the length of retention; and the uses of both DNA and the NDNAD. The UK forensic DNA database thus quickly became the largest in the world.

Prior to 2001, DNA databasing was restricted to convicted individuals, with the law requiring the destruction of records from unconvicted individuals [23]. When two criminal prosecutions based on unlawful database matches failed, an appeal to the House of Lords shone a spotlight on the NDNAD [24,25]. The 'compelling' DNA match intelligence had been held inadmissible at trial because the subject profiles were retained illegally on the database [24,25]. The Law Lords ruled however, that in such circumstances, a trial judge should exercise their discretion when admitting the evidence (so that it was not automatically inadmissible). These two cases highlighted the potential public security 'cost' of restricting the DNA database to only convicted people: the police could fail to convict guilty offenders if their DNA has been retained unlawfully. The potential for further legal challenges were also deemed likely when in 2000, Her Majesty's Inspectorate of Constabulary 'guess-timated' that at least 50,000 'unlawfully retained' samples (of non-convicted individuals) were probably on the NDNAD [26]. In response, the government quickly amended the law (again) to ensure that these profiles — belonging to individuals who had not been convicted of any crime — were now 'lawful'. With this further incremental legal reform, England, Wales and Northern Ireland now had the most inclusive DNA database in the world. DNA profiles could be taken without consent and permanently retained, from all individuals arrested for 'recordable' offences [27,28]. These profiles were to be used 'for purposes related to the prevention or detection of crime, the investigation of an offence or the conduct of a prosecution' [27].[4] Volunteers, witnesses, and victims were also included on the NDNAD if they consented, albeit this 'consent' was controversial, with the NDNAD Ethics Group reporting that the consent forms lacked adequate information [29].

The size of the database, which grew rapidly, and the inclusion of 'innocent' (unconvicted) individuals began to attract critical attention. Questions were posed about issues such as cost, effectiveness, and ethics [8,26,30—35]. Such scrutiny did not always result in the NDNAD looking like a good investment. Data wrestled out of policing authorities showed that in fact the 'success' of DNA profiling (beyond occasional high-profile cases) really depended upon the number and quality of DNA samples retrieved from crime scenes, rather than the ~40,000 individuals a month being added to the database [7]. During 2003/04, DNA was successfully recovered and the profile loaded on the database from just 5% of crime scenes examined — and only ~17% of crimes received what could be considered a scientific crime scene examination [36]. In 2007/08, about 0.35% (17,614) of the ~5 million recorded crimes that year, were detected using DNA, down from ~0.4% (19,949) in 2006/07 [37,38]. In fact, during the time of rapid expansion of the database, the number of crimes detected using the NDNAD fell in 2004/05 and did not significantly increase in the following 3 years [37,39]. Such outcomes, despite massive government investment during the 'DNA Expansion Programme' (— intended to improve the effectiveness of the NDNAD) led to the characterisation of DNA as 'a fresh filling between two slices of stale bread' [40].

The expansion of the database to include all arrestees (regardless of conviction status) raised privacy concerns and was unsuccessfully challenged through the UK courts, eventually reaching the European Court of Human Rights (ECtHR) in 2008, where it was

---

[3] The UK government required proof of familial relations to approve the asylum status of a Ghanaian family [21,22].

[4] This included minors, who if over 10 and under arrest, were treated the same as adults, if, under 10, their parents could consent to sampling [27].

ruled that the 'expansive' retention regime was disproportionate [41].[5] Domestically, the House of Lords had balanced the competing interests of public security and individual privacy in favour of the public [42], but the '*Marper*' ruling in Europe demanded reforms to the legislative regime governing the NDNAD [41], eventually resulting in the enactment of the Protection of Freedoms Act 2012 (PoFA) [43]. The NDNAD today remains governed by these rules introduced by PoFA, with DNA samples from all individuals to be destroyed following DNA profiling or within 6 months of collection.[6] The DNA profiles of convicted adults and some juveniles are indefinitely retained while juveniles convicted of a first minor offence with a sentence of less than 5 years can be retained for 5 years plus the length of sentence. For unconvicted individuals, DNA profiles of those charged for a serious offence are subject to an automatic 3 years retention plus a 2 years renewal with consent of the court. The same rule applies to those arrested for a serious offence (but not charged) but the first 3 years retention requires consent of a Biometrics Commissioner established under PoFA. Other temporal/short retention periods apply to those issued with a penalty notice for disorder or where a 'national security determination' is made.[7] All other arrestees and/or charged individuals are subject to retention until the conclusion of the police investigation or any proceedings.[8]

Underlying the *Marper* decision was a lack of empirical evidence demonstrating the utility of retained DNA records from unconvicted individuals. Ten years on, this knowledge gap has not been closed. Decisions on who should be included on the database and how long to retain their data to maximise the effectiveness of the database, are still not grounded in evidence. Whilst the match rate of the NDNAD has increased following the introduction of PoFA, this statistical data is limited in its ability to demonstrate public security outcomes. Attempts to date to measure 'effectiveness', with outcomes identified from the literature are discussed in the next section.

3. Measuring 'effectiveness'

3.1. a. Indicators for 'effectiveness'

Analysis of the literature reveals seven 'outcomes' or 'indicators' by which the effectiveness of a forensic DNA database could be assessed. Fig. 1 summarises these outcomes.

According to section 63T of the Police and Criminal Evidence Act 1984, one of the primary aims of the UK NDNAD is to assist the police to solve crime ('crime solving capacity'). This should mean an increase in case resolutions, normally considered as securing convictions of offenders, indicates the crime solving capacity of the NDNAD. However, Bieber [50] details four broad reasons why convictions may not be an accurate measure: variation in the treatment of DNA hits; problems associated with the trial or evidentiary criteria; failure/inability of individuals to testify at trial; and time constraints. Besides these challenges, it is very rare that a DNA hit is the sole predictor of conviction since it is most

often considered alongside other evidence. Furthermore, 'case resolution' should be interpreted broadly and could encompass: the contribution of DNA hits to the elimination of suspects; linking of crimes; and saving time and resources by speeding up the resolution of cases that may have been resolved eventually without DNA [50]. Thus 'convictions' are a far too simplistic and narrowly conceived measure of the 'crime solving capacity' of a database.

The lengthy and/or frequent incapacitation of offenders through imprisonment or other incapacitating disposals is assumed to reduce crime rates [47,50,54–57]. The incapacitation effect of DNA databases has thus been measured by some authors by assessing crime rates [47,48,58]. However, it remains very unclear whether the retention of DNA data and its downstream incapacitation effects can lead to a discernible reduction in crime, particularly when most criminal justice disposals are very short or do not involve a custodial sentence. Further, high rates of recidivism among convicted individuals, perhaps makes it more likely that crime rates may increase subsequent to their conviction, or at least would not decline measurably.[9] It also needs bearing in mind that the proportion of crimes that potentially could be, or are in fact 'resolved' utilising DNA database hits is very low,[10] so any incapacitation effect directly attributable to a DNA database is going to barely register statistically (particularly in low crime areas). Finally, not all crimes are reported, much less detected.[11] Further, crime rates are impacted by numerous variables including socio-economic factors and available statistics on crime rates are acknowledged to be crude estimates. These reasons make it problematic in measuring the overall independent role of DNA databases in crime reduction [50]. Incapacitation effects may thus be a weak outcome of the effectiveness of DNA databases. It is undeniable however that many serious criminal offenders will have been identified using a DNA database and their subsequent incapacitation will have prevented some crimes. Its appeal for advocates of DNA databasing, with the allure and simplicity of the issue when garnering public support thus remains despite serious limitations. Hence it cannot be ignored as a potential outcome when considering the effectiveness of DNA databasing.

Several reviews have highlighted the deterrent effect of DNA databases as an indicator of effectiveness [30,50]. Whilst Doleac [47,48] has attempted to measure deterrent effects of databases, empirical evidence to adequately demonstrate this effect remains scarce. Proposed research methods to estimate deterrence effects include the measurement of perceived deterrence among first-time arrestees and convicted individuals, and assessment of criminal records [61]. The comparison of the different groups may help determine whether the retention of DNA data can modify

---

[5] The application to the ECtHR had been made by two unconvicted individuals, 'S' (a minor at the time of sampling) and Marper, both of whom had requested for the destruction of their biometric records (DNA and fingerprints) following their acquittal and discontinuation of proceedings, respectively.

[6] Samples — the human material from which the DNA profile was derived, used to be retained as well as the computer profile.

[7] A 'National Security Determination' is a writ by a Chief Constable to extend the retention period of DNA records from an unconvicted individual on national security grounds.

[8] For detailed discussion of the implementation of PoFA, see Amankwaa and McCartney [15].

---

[9] For example, a study comparing recidivism among repeat felons before and after the introduction of the US CODIS Database in 1998 found similar results (51% vs 49%). See Gabriel et al. [44].

[10] The 'crime solving' capacity of any DNA database is limited to resolving those crimes where DNA is present and detected (and leads to a 'hit' on a database). For example, this will exclude almost all so-called 'white collar' crime that will rarely involve DNA, and 'cybercrime' will almost certainly not involve DNA. So a large proportion of recorded crime will not have a 'crime scene', or will not have the potential for DNA to play a role in the investigation [59]. See later the 'link to outcomes' measures (section 3.2.2).

[11] See Office for National Statistics [60]: there is an acknowledged chasm between the number of crimes recorded by the police, and the number of crimes that may actually occur. For example, in 2017 according to the Crime Survey of England and Wales estimate, there were 10.8 million crimes committed against adults aged over 16 (thus not including crime against businesses). However, in that year the police recorded 5.2 million crimes. In year ending March 2017, the police closed almost half (48%) of offences with no suspect identified. This proportion varies by crime type with 68% of criminal damage and arson offences closed with no suspect identified, compared with around 1 in 20 (6% or lower) rape or drug offences.
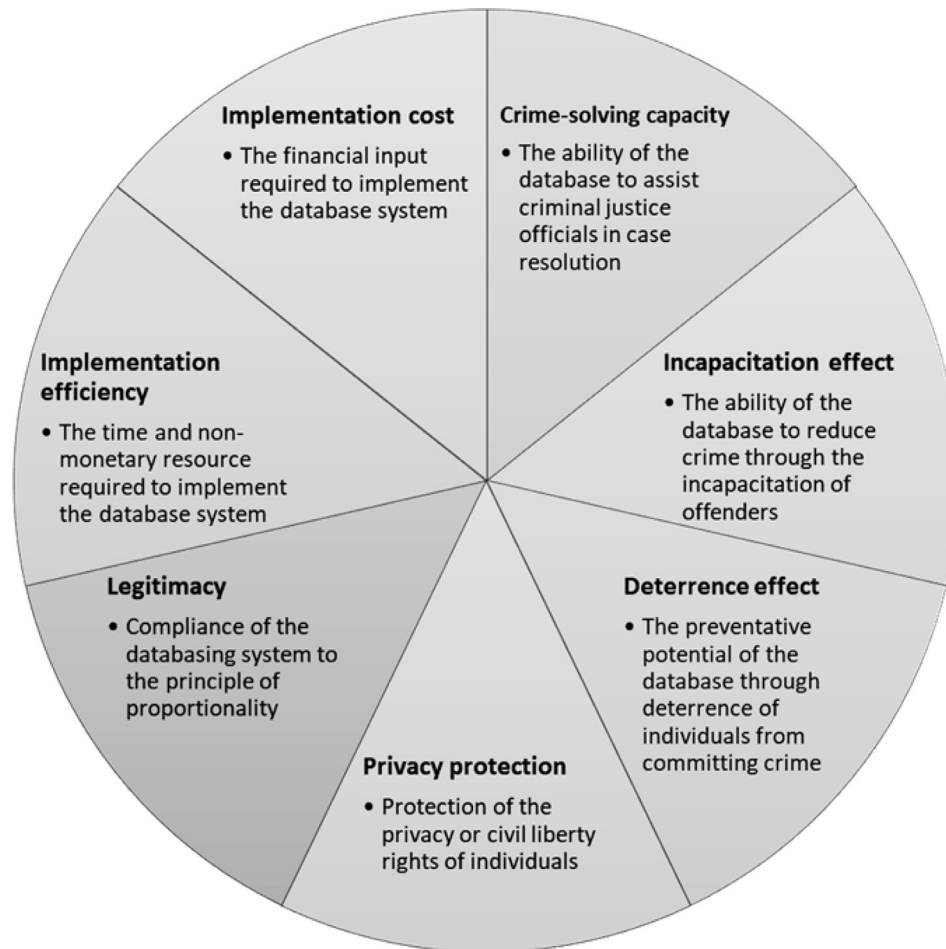
Fig. 1. Key 'indicators' of an effective national forensic DNA database based on assessment of existing literature [7,17,26,44–53].

individual behaviour and promote desistance, with preliminary studies showing that offenders on the DNA database are likely to demonstrate subsequent 'good' behaviour [58,62]. Critics of this indicator argue that it may be impossible to prove this effect due to several confounding variables. For example, recidivistic offenders may change their modus operandi, offending behaviour, or move location to prevent detection [34,50]. Like the incapacitation effect, the deterrence effect of DNA databases may then be a weak indicator of success. However, given the emphasis on this hypothetical benefit of databases [42], deterrence effects should be examined more closely.

Privacy has been a central issue in discussions about the effectiveness of DNA databases with the retention of data of innocent individuals remaining contentious [34,63–69]. The literature clearly shows that an effective DNA database should be lawful and ethical. It's public protection goals in resolving, reducing or preventing crime must be balanced with the human rights of individuals including the right to privacy. Hence, a true measure of the effectiveness of DNA databasing should include how well it protects the genetic privacy of individuals (*privacy protection*) and its proportionality to public security interests (*legitimacy*). These indicators should, therefore, be considered in assessing the success of databases.

Finally, the time, effort and cost of implementing the DNA database system should be justified. In addition to direct and indirect costs of running the NDNAD (including sampling and processing of DNA), new financial costs have been generated by

the PoFA regime. Prior to the implementation of PoFA, the Chair of the NDNAD Strategy Board stated that PoFA may introduce 'a significant administrative burden' [70], and involved: the establishment of the Office of the Commissioner for the Retention and Use of Biometric Material[12]; the destruction of DNA records; introduction of DNA retention assessment procedures; changes in IT infrastructure; DNA retention compliance checks; changes in DNA retention practices; establishment of Biometric Retention Units; and education of relevant stakeholders [15,43]. Assessment of implementation efficiency and implementation cost is important because DNA databasing is only one aspect of crime control. There are other equally, or more important aspects of police work (and that of other agencies) which also require resourcing.

In summary, the question about the effectiveness of the NDNAD could be answered by testing the NDNAD against the seven identified outcomes or indicators outlined above: crime-solving capacity, incapacitation effect, deterrence effect, protection of privacy, legitimacy, implementation efficiency and implementation cost. Despite the apparent clarity of these indicators or outcomes, there have been difficulties in identifying specific 'measures' or isolating metrics that could be used to measure these seven outcomes.

---

[12] The annual budget for the Office of the Biometrics Commissioner is approximately £300,000 [51].

3.2. b. What is currently measured?

The case resolution effectiveness of forensic DNA databases can be framed within two contexts ("effectiveness context"):

1) its contribution to the resolution of crimes where DNA from the crime scene is loaded on the database ('DNA-related crime'); and
2) its impact on the resolution of all recorded crime.

3.2.1. i. Effectiveness context one: DNA-related crimes

In the first context, several approaches have been taken to measure the 'effectiveness' (performance or success rate) of forensic DNA databases, the majority focussing upon matches generated ('hits') and investigations aided ('link to outcome'), both described as output metrics [50]. 'Hits' are matches obtained from the database, either between known individuals and crime scene samples or matches between different crime scene samples. These can be further categorised by offence type or for different categories of individuals. Where a DNA hit contributes to the investigation of an offence, this is counted as an investigation aided; the United States Federal Bureau of Investigation (FBI) uses this metric.[13] In the UK, the rate at which DNA was 'linked to outcome' is reported, i.e. associated with a suspect being charged or cautioned for an offence for example.

3.2.1.1. Match rates.

The NDNAD Strategy Board reports the 'match rate', which measures the chance that a crime scene profile loaded on the database matches the DNA data of a known individual. This shows the 'potential' crime solving capacity of the database. The match rate can also be computed for crime scene profiles or the chance of a loaded subject profile matching a stored crime scene profile. The match rate is calculated by dividing the number of matches between loaded crime scene profiles and retained subject profiles by the total number of crime scene profiles loaded. As of December 2018, the NDNAD holds >6 million subject profiles and >600,000 crime scene profiles [72]. The "match rate" of the database reached its highest level from 2013—14 to 2017—18 (62%—66%) [73]. This has been interpreted as an indication of improving performance although the number of loaded subject and crime scene profiles have decreased [59]. Further, available records show that the proportion of crimes examined for forensic evidence has fallen from 12.8% in 2014/15 to 11% in 2015/16 [74,75]. This suggests that whilst the match rate may be high, the overall contribution of the database to the resolution of all crime remains low.

One of the limitations of match rates is that they do not show how the hits contribute to the progress or outcome of criminal investigations. A DNA hit does not show that the subject is the offender and there are many reasons why the DNA of an individual may be found at a crime scene. DNA can be transferred directly or indirectly and issues of persistence of the deposited material may complicate the interpretation of the evidence [76,77]. In all cases, the hit needs evaluation in the context of the alleged crime and other evidence, yet whether the hit was probative is not captured by match rates. Secondly, a DNA hit may not be relevant since the identification of the offender may have been established by other means, for example eyewitness account, CCTV or fingerprinting, assuming identity was ever in doubt (in that they were not caught

'in flagrante'). Thirdly, the database also includes duplicate profiles (currently >13% for the NDNAD) [72]. The match report does not differentiate between duplicate hits and genuine hits. These factors diminish the value of the match rate metric in assessing the success of the NDNAD in the first effectiveness context. The shortcomings of the match rate thus make it necessary to develop further output and outcome metrics, leading to attempts to collect data on the link between hits and case outcomes.

3.2.1.2. 'Link to outcome'.

In April 2014, a new framework, the Recorded Crimes Outcomes Framework (RCOF), was introduced to facilitate the police recording of case outcomes [74]. Eight outcomes are considered under RCOF: charged or summonsed, caution — youths, caution — adults, deceased offender, penalty notices for disorder (PND), cannabis warning and community resolution. The RCOF rate is a percentage of loaded crime scene profiles linked to a counted outcome following a match on the NDNAD. According to the NDNAD Strategy Board, the RCOF rate for 2014/15 was 41.6%, representing 13,375 of 32,168 crime scene profiles loaded in that fiscal year [74]. The RCOF rate for 2015/16 was 50.4% (11,378 of 22,584 crime scene profiles) [75]. When stratified by crime type, homicides (81.9%) had a higher RCOF rate than rapes (55.6%), vehicular thefts (40.8%) and domestic burglaries (40.2%) in the 2015/16 period. Although no statistical tests were carried out, the figures suggest that the database may be more useful in investigating or resolving violent crime than property crime. The 2016/17 report of the Strategy Board does not provide data on the RCOF rate for that period. There are presently no records on the number of convictions aided by the NDNAD since DNA-only cases are rare [78]. Clearly, the RCOF rates show that not all DNA hits are linked to a counted outcome, with a considerable difference between the match rate and RCOF rate (for example, match rate of 63.3% vs. RCOF rate of 50.4% in 2015/16) [75]. Although the RCOF rates provide further insight on the usefulness of DNA hits, it still lacks clarity on how the matches contribute to crime resolution and the outcome of cases. The available data, however, shows that, upon further filtering, the proportion of profiles loaded on the database that lead to case resolution after a hit may be lower than the match rate and RCOF rate.

3.2.2. ii. Effectiveness context two: all recorded crime

The second "effectiveness context" of the NDNAD is its impact on the resolution of all recorded crime. According to the Biometrics Commissioner [59], DNA was "linked to outcome" in just 0.3% of all recorded crimes in England and Wales in 2015—16. As noted previously, this low rate remains unchanged since the database was created in 1995. Even in cases where DNA might be expected to be important, DNA is still, for the most part, insignificant as a crime-solving tool. For example, in all recorded rapes, just 0.6% have a DNA hit linked to their outcome, and in all recorded domestic burglaries, 1.4% [59]. It is most helpful in all recorded homicides, where it is linked to outcomes in 8.4% of cases [59]. Yet even when DNA is linked to outcome, the reality is that the police often already had a prime suspect. DNA is simply used to confirm their identity (so-called 'warm hits'[14]) and help construct a prosecution case (or persuade the suspect to plead guilty and/or accept a caution).

The courts in England and Wales have now established that "where DNA is directly deposited in the course of the commission of a crime by the offender, a very high DNA match with the defendant is sufficient to raise a case for the defendant to answer"

---

[13] The United States National DNA Index (NDIS) holds >13 million profiles from offenders, >3 million from arrestees and >900,000 from crime scenes; the number of hits generated from the NDIS was >451,000 as of January 2019. This has contributed to >440,000 investigations [71].

[14] A warm hit refers to a match between a crime scene profile and the profile of an individual already identified by other means such as fingerprinting [9]. The hit is only used to confirm identity in such cases.

[79]. Whilst this indicates that "DNA-only" cases could now go to court with no other evidence, this still depends on the overall circumstances of the case [80]. Further, while a DNA match might have featured during a trial, it remains unknown whether the jury placed any weight on the DNA evidence, considering the context of the case and issues of transfer and persistence [77]. It is difficult then, to exclusively link a conviction to DNA evidence. Match rates and 'link to outcome' metrics then fail in providing clear answers to questions concerning the overall value of DNA databasing to solving DNA-related cases and its contribution to solving all recorded crime.

3.3. c. Extant evidence for the effectiveness of DNA evidence and DNA databases

Systematic evidence to demonstrate the aggregate value of DNA databases is presently lacking. This vacuum is perhaps explained in part by a lack of demand for an evaluation of DNA databases or difficulties due to the unavailability and inconsistency of data [45]. This section draws on findings from the limited research undertaken which relates to the effectiveness of DNA databases in different jurisdictions. Three groups of studies focussed upon database performance/effectiveness or efficiency have been published. The first group analyzes the overall contribution or value of DNA evidence and/or DNA databases to the detection of all crime. These studies point to the marginal significance of DNA evidence and/or databases in crime detection or clearance overall. The second group of studies examine the impact of DNA evidence and/or the DNA database on crime detection or prevention in crimes that involve DNA versus those that do not involve DNA. This group of studies show that crimes where DNA evidence is available are more likely to result in a detection or case resolution. Finally, the third group of studies consider creating statistical models to systematically evaluate the performance and efficiency of DNA databases. Only crude estimates of performance or effectiveness can be determined with the current models available.

3.3.1. i. Contribution of DNA evidence and DNA databases to case resolution

In 1999, Tracy and Morgan [81] assessed the overall effectiveness of DNA typing/databasing in the United States by analysing crime statistics, clearance rates, prosecution efficiency and cost-effectiveness. Overall, the authors concluded that the actual impact of DNA typing/databases on crime may be lower than public expectations – which suggests strong support for DNA databases [82]. Of all indexed serious crimes (17.8% of all crimes) reported in the FBI Uniform Crime Report (1997), 87.6% were crimes against property (CAP) whilst 12.4% were an offence against the person (OAP). The clearance rate of OAP (48.3%) was higher than CAP (17.5%). This observation was attributed to the fact that OAP usually involves victim-offender interaction and may readily yield DNA evidence to improve detection rates. For less serious or non-indexed crimes (which make up 82.2% of all crimes), only 10.2% are OAP. Analysis of 'DNA prosecutions' showed that DNA use is restricted to OAP such as violent and sexual crimes. This data suggests that DNA evidence contributes little to the resolution of all crime and may be more valuable in serious crime. It was also found that DNA is used more often in populous areas though more crimes (64%) are prosecuted in less populous areas. Emphasising the fact that DNA database initiatives are labour or resource intensive, the expansion of DNA databases to cover all arrestees and the entire population was thought to be cost-ineffective as well as having negative civil liberty and ethical implications.

In England and Wales, Burrows and Tarling [32] investigated the contribution of forensic evidence including DNA in the detection of property crime (burglary and vehicle crime). The study used data available from the Home Office 'Pathfinder Project' (June 2000–May 2001) that focussed on two police forces, Greater Manchester Police and Lancashire Constabulary. Additional information from Morgan Harris Burrows' evaluation of the DNA Expansion Programme was also included in the analysis. Of approximately 1.8 million property crimes committed every year, it was estimated that 612,000 (34%) are visited by crime scene investigators. Approximately 18% (110,040) of visited scenes yield DNA (either SGM+ (6%) or Low copy number (LCN) DNA (12%)). The profiling success of the crime scene DNA was found to be 60% for SGM + DNA and 18% for LCN DNA. The match rate for SGM + DNA was 73.3% whilst LCN DNA was 66.7%. Overall, 4% of visited scenes led to the detection of crime using DNA matches. It was estimated that ~10% of property crimes are detected by the police and both fingerprints and DNA contribute to about 33.3% of these detections. The sole contribution of DNA and/or the NDNAD to the clear-up rates was not estimated. Nevertheless, the study showed that though DNA evidence appears to play a crucial role in property crime, its overall contribution to crime resolution remains very low.

Similar to the results of Burrows and Tarling [32], other reviews focused on property and serious crimes have found a low contribution of databases in resolving crime. In England and Wales, the estimated contribution was found to be ~1% for property crimes as of 2002/2003 [83] and 15.10% for all murders[15] in 2009/10 [84]. The property crime review relied on publicly available data on the potential number of DNA-related convictions versus the number of reported property crimes as of 2002/2003. The murder crime study was based on the opinion of Senior Investigating Officers [84]. In the Kennemerland police region of the Netherlands, Mapes et al. [85] found that the national DNA database contributed to 1% and 3% of property crimes and serious crimes (such as murder and sexual assaults), respectively. This study utilised data from forensic reports in 2011. Briody and Prenzler [83] also examined the potential effect of DNA databases on property crime levels in New South Wales, Australia. The evaluation report of the Vendas Police operation in 2002/2003 was analysed. There was no significant reduction in property crime levels before and after the implementation of improved forensic biometric capabilities (DNA and fingerprints). In the United States, Wells et al. [86] found that only 1 out of 104 CODIS hits proceeded to charge in untested sexual assault kits. The study examined 491 kits from the Houston Police Department and hit outcomes were assessed via interviews rather than actual follow up of cases. Whilst the findings from the above studies are crude estimates and based on "old" DNA analysis methodologies, they are generally consistent with previous reports and the current outlook of the UK NDNAD as a 'marginal' contributor to the resolution of all crime [59,87,88].

The findings generally suggest that DNA databases are more useful in solving a specific type of cases and has a potential impact on offenders of certain characteristics. It is imperative that evaluative studies on the actual effectiveness of databases are carried out to identify characteristic patterns in the small number of applicable cases. This will ensure that databases are cost-effective and focused to assist the Police.

3.3.2. ii. Comparison of cases involving DNA and cases without DNA

The 'ultimate' outcomes of DNA hits, in terms of demonstrating how DNA contributed to a criminal case and how the case was resolved, are preferable over proxy output metrics such as number of matches, number of investigations aided and match rates [89].

---

[15] This estimate is reported in an unpublished National Policing Improvement Agency study [84].

Some studies have compared the outcome of criminal cases involving DNA evidence and cases without DNA to understand the impact DNA hits have on cases.

In Australia, Briody [90—92] assessed the effects of DNA evidence in selected sexual and property crime and homicide cases between 1994 and 2001. The Australian National Criminal Investigation DNA Database (NCIDD) was established in April 2001 [93]. Thus, the selected cases were those in which DNA testing confirmed (or not) the involvement/identity of already identified or charged suspects. Data was analysed using a control-comparison approach to compare: 201 sexual offences with DNA to 98 cases without DNA [90]; 100 property crimes with DNA to 100 non-DNA cases [92]; and 75 homicide DNA cases versus 75 non-DNA cases [91]. In all three types of cases, it was found that those involving DNA are more likely to reach court than non-DNA cases. DNA evidence was associated with more guilty pleas in property offences but not sexual crimes and homicides. Sexual offence cases with DNA evidence were associated with more guilty verdicts by a jury, and more and longer custodial sentencing. The three studies suggest that coupled with a well-targeted and effectively utilised national DNA database, the judicial outcomes of sexual and property crimes and homicides could be improved.

In a similar prospective randomized study in the US, property crime cases involving DNA analysis/a CODIS hit was associated with an increase in suspect identification, arrest rate and prosecution rate [49]. The study analysed a total of 2160 cases between 2005 and 2007 in five cities in the US. Biological evidence was recovered from all the cases included in the study. The cases were randomly assigned into two groups: treatment group (DNA analysis group: $n = 1079$) and control group (traditional investigation group (including fingerprint analysis): $n = 1081$). Suspect identification, the arrest rate and prosecution rate were higher in the treatment group (31%, 21.9% and 19.3% respectively) than the control group (12.8%, 10.1% and 8.1% respectively) [49]. Analysis of the cost-effectiveness of the 'DNA-assisted arrests' revealed an average cost of approximately $14,000 across the different states.[16] According to the authors, this cost was higher than traditional investigation such as fingerprint analysis. Hence, though DNA may be effective in resolving crime, investment in DNA databases should be limited to those crimes where DNA is useful. Further, there should be consideration of the availability of resources for other policing work.

Lastly, Cross et al. [94] researched the impact of DNA on arrest in sexual offences. The study reviewed 528 cases from Massachusetts between 2008 and 2010. It was found that DNA could have been influential in only 8 cases where arrests occurred near to the time or after laboratory results were provided. This shows that the value of DNA profiling and databasing depends on when a profile or match is produced and what influence it can then have through the justice process. If a profile is generated more quickly and/or immediately loaded on the database, suspects may be identified and processed speedily using DNA evidence (i.e. in such DNA-related cases where identity of the offender is unknown). In this regard, the introduction of rapid DNA testing may be useful in enhancing the potential of databases [73,95—97]. However, as shown in this study, the police may use alternative means to identify and subsequently arrest suspects. These alternative measures may be more effective than DNA profiling and databasing combined. Hence, the output/outcome of DNA analysis and databases may be low [98]. There is limited information on how DNA databasing compares with DNA profiling alone (i.e. without the use of the database) and other detective resources [98]. Such an

analysis is relevant because it will inform policy decisions on the investment and scope of DNA profiling and databasing.

Cross et al. [94] also compared the bulk of cases (91.5%) where the arrest occurred before DNA results and the DNA-related arrests. It was found that the DNA arrest cases were more likely to link to other crimes on the CODIS database to identify serial offenders. Though limited in the number of cases, this study seems to suggest that retaining DNA data from sexual crimes may be relevant.

3.3.3. iii. Models to evaluate the performance/effectiveness of DNA databases

Gabriel et al. [44] developed three performance metrics to evaluate the effectiveness of DNA databases: 1) Significance of a database hit; 2) case progression and judicial resolution; 3) potential reduction of future criminal activity. These three metrics were then tested using 198 DNA cold hits[17] obtained by the San Francisco Police Department, USA, from 2001 to 2006. For the first metric, the study found that 90% of DNA hits aided police investigations including the identification of suspects. Approximately 40% of the cold hits reached judicial resolution including conviction, guilty plea or parole revocation. About 28% of the cases were still under investigation or yet to be tried in court. It was expected that the progress of pending cases could lead to ~70% judicial resolution. When broken down by offence type, the potential case progression/judicial resolution rate for sexual cases ($n = 110$) was ~50%, homicide ($n = 24$) was ~91%, burglary ($n = 42$) was 88% and other crimes was 40%.

For the third performance metric, the criminal history of 12 recidivistic sex felons was analysed. On average, each felon committed ~25 offences including serious and minor offences. The average for sexual offences was ~4 per individual. Compared to published data indicating an average of 8 throughout the criminal career of serial sex offenders [44,99], the authors estimated that more than 40 offences[18] could be prevented by DNA databasing through its incapacitation effect. However, it was found that the proportion of offences committed by the 12 felons before (51%) and after (49%) the introduction of the CODIS national DNA database in 1998 was roughly similar. This suggests that the recidivistic behaviour of offenders may inhibit the crime reduction ability of DNA databases. For example, 45% of sexual crimes were committed during probationary periods of the felons.

Walsh et al. [100] also developed two DNA database performance metrics: Match/hit rate (HR: crime-person matches per crime scene profiles loaded) and 'return index' (RI: total number of matches (NH) per total number of profiles (NS)). The two metrics were tested using publicly available data from the UK NDNAD, CODIS NDIS (USA),[19] California SDIS[20] and the Canadian National DNA Databank (NDD-Canada) prior to 2008. Initially, the growth in the size of the databases was analysed. The UK NDNAD, CODIS NDIS and SDIS were found to fit a quadratic model with positive changes in growth linked to government/state policy (the DNA Expansion Programme (UK), Presidents Initiative on DNA (USA), and Proposition 69 (California)). The growth of the Canadian NDD was found to closely fit a linear model, demonstrating consistency in

---

[16] The cost covers arrests that would not have occurred without DNA [49].

[17] A cold hit refers to a match between a stored subject profile and a profile from a crime scene where the perpetrator or suspect is unknown [9].

[18] I.e. average of four additional offences per individual multiplied by 12 felons.

[19] The CODIS National DNA Index (NDIS) is the national DNA database of the United States. The NDIS was established in 1998 under the custodianship of the FBI (see FBI [101]).

[20] DNA databasing in the United States is operated at three tiers: National, State and Local DNA Index Systems. The California State DNA Index System (SDIS) is the database for the state of California. It is the largest state database with more than 2.9 million profiles as of January 2019 (see FBI [71]).

sampling/retention regime. The RI and HR were found to be independent of database size, with no correlations observed. Though the study establishes a model to assess effectiveness, the implications of the study are limited by the source of data used, the differences in what counts as a hit, and lack of detail about the characteristics of the databases examined. For example, it is not clear whether only 'cold hits' were assessed or all hits. If the main purpose of a database is to solve cold crimes, assessing all hits (cold and warm) may be inappropriate.

In 2010, Walsh et al. [45] published an inferential model for determining the performance and financial efficiency of forensic DNA databases. The performance formula, referred to as the return index (RI) is given by $RI = \frac{H}{NC}$; where H is the number of matches/ hits, N is the number of reference profiles in the database and C is the number of crime scene profiles on the database. The variable H is given by the formula: $H = \frac{\alpha N \times \omega C}{M}$; where α refers to the average fraction of active offenders on the database, ω refers to the average fraction of actual offender crime samples, M is the proportion of active offenders from the population. The RI model was tested using publicly available data from the UK NDNAD, the USA CODIS and the Canadian NDD. A plot of H versus NC found that the number of matches initially increases with the product of the number of reference and crime scene profiles, but plateaus over time. The reasons attributed to this observation include the retirement of active criminals and/or incapacitation of offenders making them inactive.

The DNA Working Group (DWG) of ENFSI [102] criticised the Walsh Return Index, noting that the model suggests smaller databases are more effective than larger databases. This is because the RI is inversely proportional to the size of the database (NC). The ENFSI Working Group proposed two alternative performance metrics. The first metric is H/C — the number of matches per number of crime profiles loaded on the database. This formula demonstrates the 'potential' crime-solving capacity of the database and indicates whether the sampling of crime scenes is efficient. It is hypothesised that as the size of the database increases, H/C will increase. The second metric is H/N — the number of matches per number of reference profiles in the database. This metric shows whether the database is representative of the active criminal population and/or irrelevant reference profiles are not on the database. A test of the H/N metric on European databases show that the England and Wales NDNAD has the highest value (0.44) as of June 2016 [103].

In 2013, Santos et al. [104] classified the inclusion/retention regime of 22 European Union member states including the UK and assessed their database performances. The study used the H/N metric to evaluate performance. Two types of regimes emerged from the analysis: restrictive and expansive regimes. The first was generally characterised by limited temporal retention of DNA records of suspects and individuals convicted of a serious offence. The expansive system generally allows longer periods of retention and/ or indefinite retention for suspects and individuals convicted of any crime. Respective match rate data was extracted from the 2011 report of the ENFSI DWG. The then retention regime of England and Wales was expansive, allowing indefinite retention of all arrestees whether convicted or not. The study compared the smaller, restrictive databases with the bigger, expansive databases. Using the Mann-Whitney test, the study found no statistically significant difference in the median H/N between the restrictive (0.095) and expansive (0.100) systems (p > 0.5). This suggests that the type of inclusion/retention regime, (and ergo the size of the database), is unrelated to the performance of the database.

Although Santos et al. [104] offer a basis for comparative analysis of national databases, many factors affect the performance metric used including variations in the implementation of legal systems, the age of the database, previous changes in law, and differences in counting database hits. Moreover, the classification of the legal systems may be too broad both within and between the two categories. A further useful analysis to determine the impact of the law and the value of DNA databasing could be filtering the performance ratio by retention category, retention time, and crime type in a single state [105,106]. Though there were genuine reasons for using the H/N metric, analysis of the crime-solving match rate — H/C could be useful in demonstrating the potential contribution of the database to public security. A research programme using both H/C and H/N for different retention regimes, inclusion criteria and retention lengths in a single state could offer a new understanding of the potential effectiveness of databases.

Finally, another model used to assess database effectiveness is the instrument variable (IV) strategy developed by Doleac [107]. The model was used to test the effect of DNA databases on crime in the United States [107]. Firstly, the study analysed the criminal history of offenders before and after DNA expansion in 7 states. The probability of re-convicting serious violent and property offenders was reduced by 17% and 6%, respectively, within 5 years of expansion. Secondly, the size of the DNA database was compared to crime rates from 2000 to 2010. The growth of the database was associated with 7—45% and 5—35% decrease in violent and property crimes, respectively. Analysis of the cost-effectiveness of using DNA databases to investigate serious offences showed lower marginal cost than other alternative crime-fighting measures (<$600 versus $7600 (longer sentences) or $26,300—62,500 (police officers)). The results of this study were consistent with a similar study by Doleac et al. [108] that assessed the effectiveness of the Denmark DNA Database (DDD) using the IV strategy. An expansion of the DDD in 2005 was associated with a subsequent reduction in recidivism rate by 26% within 5 years and an increase in crime detection by 0.09 crimes.

The IV strategy was also used by Doleac [109] to test the cross-state effect of DNA database policies in the USA. The study compared DNA database size and crime rates among states. It was found that an increase in the total size of databases in external states increases violent (0.0001) and property (0.0003) crime rates in the reference state (p < 0.05). Also, an increase in the size of a nearby state's database (<500 miles) increases violent (0.0011) and property (0.0063) crime rates (p < 0.01). A similar trend was observed when the total profiles of external states were weighted by distance. Expansion of a nearby state database (100 miles) results in higher violent (0.0012 versus 0.00004) and property (0.0042 versus 0.00004) crime rates than far away states (3000 miles). It was hypothesised that expansive DNA database policies in one state lead to migration of criminals whilst restrictive policies draw in criminals. An alternative effect is that the former lead to incapacitation or deterrence of crime thereby reducing crime across states. The results of the study demonstrated a negative cross-state effect. It was recommended that to limit migration of criminals, states must ensure equivalency in their DNA database policies.

In summary, the three IV strategy-based studies demonstrate that expansive DNA databases could reduce crime rates and limit criminal activity. However, the results should be interpreted cautiously since the data relied upon were estimates — which may not be representative of the actual effects of DNA databases. Secondly, there are many confounders associated with criminal activity and crime rates in a specific state including age, gender, family structure, cultural context, educational level of residents, alternative law enforcement resources, employment and other crime-reduction policies. These factors were not accounted for in the studies. Moreover, the usefulness of the DNA and the database applies to a small proportion of all crimes as noted in section 3.3.1.

4. Conclusion: the UK NDNAD: a good return on investment?

Operating the UK National DNA Database costs the government ~£2.5 m a year, while individual police forces must meet the (not insignificant) costs of crime scene investigations and DNA analysis. Yet what evidence exists shows that while DNA databases may offer slightly improved detection or conviction rates, the overall contribution of DNA databases to public security may be negligible. The (limited) data from the UK can certainly be summarised in this way. Furthermore, models developed to assess the effectiveness of databases in the small proportion of crimes where they are useful only provide estimates that may not reflect actual effectiveness. Therefore, considering the cost of operating the NDNAD, the question remains over whether the database is providing a good 'return on investment'. The ENFSI DNA working group suggest that the UK's NDNAD is closest to achieving a database with the data of the active criminal population and the current PoFA retention regime may be more effective than other regimes across Europe [103]. But while an expansive inclusion/retention regime may increase the periods of incapacitation of serial offenders through frequent detection and conviction, DNA databases may interrupt criminal activity for just a short period, and intractable recidivism may limit its full public security potential.

Expansive regimes also pose a threat to civil liberties and human rights, which must be accounted for in the operation of databases. Casting a database as 'effective' when it may lack public support, or is contested on ethical grounds, is problematic. Maintaining national DNA databases requires vigilance over the adequacy of safeguards in protecting rights to privacy and avoiding negative social impacts, particularly in light of scientific, technical, and operational developments [15], albeit these debates are not the focus of most research on 'effectiveness' and have not been entered into in depth here. Suffice to say, that the ethical credentials, and public confidence in a DNA database and its operation, are vital components of a comprehensive measure of a database. The utility of forensic databases must only be maximised at the same time as minimising risks of abuse or other potentially harmful effects.

Based on the findings from this review, it is recommended that oversight bodies such as the Strategy Board develop ongoing programmes to assess the *end-to-end probative value* of NDNAD hits. Assessment of actual effectiveness should be a *statutory requirement* as part of the annual reporting of oversight bodies. Key indicators of the overall effectiveness of the NDNAD should include *administrative data* that demonstrate the crime-solving capacity of the NDNAD, deterrence and incapacitation effects, implementation costs and efficiency. Additionally, a national *DNA Database Perception Index (DDPI)* should be established. The DDPI should be designed to assess the perception of the public and stakeholders on regular basis and should cover the benefits of the NDNAD and aspects of the database that cannot be measured directly such as proportionality and the protection of civil liberties.

Until such time as data along these lines are available, we remain a long way from gathering the evidence that could establish how effective the UK NDNAD is, and whether the taking of half a million DNA profiles a year and the storing of over 6 million profiles is worthwhile. What we do know is that the limited knowledge of the effectiveness of DNA continues to be a prominent theme in the annual reports of the UK's Biometrics Commissioner [51,59,110]. The public may be willing to sacrifice some of their privacy for societal benefits, but if the benefits cannot be evidenced, or remain elusive, then that sacrifice may be questioned [82]. This knowledge gap then remains critical as understanding effectiveness enables measures to be implemented to maximise the utility of the NDNAD. In the absence of meaningful statistics and case evaluation, it is hard to deduce the optimal scale and arrangements for an effective DNA database that enhances public security while protecting individual rights. There therefore needs to be continuing public debate over the police use and retention of DNA. Far from being a catch-all solution to modern crime, a case still needs to be made for DNA evidence — apart, of course, from on TV detective shows.

Conflicts of interest

None.

References

[1] BBC News, Melanie road murder: man jailed for 1984 melanie road murder. BBC [internet]. 2016 May 9 [cited 2018 Dec 6], Available from: https://www.bbc.co.uk/news/uk-england-somerset-36245888.

[2] C. Hayhurst, Melanie road murder: how a remarkable 32-year-old murder cold case was solved. The independent [Internet]. 2016 May 10 [cited 2018 Jun 20], Available from: http://www.independent.co.uk/news/uk/crime/melanie-road-murder-how-dna-collected-in-1984-solved-the-32-year-old-case-with-christopher-hampton-a7022056.html.

[3] E. Pearson, Victorians under arrest to be DNA swabbed under new legislation [internet]. The age. 2018 [cited 2018 Aug 8], Available from: https://www.theage.com.au/national/victoria/victorians-under-arrest-to-be-dna-swabbed-under-new-legislation-20180619-p4zmet.html.

[4] IAG, Report of the Independent Advisory Group on the Use of Biometric Data in Scotland, Scottish Government, Edinburgh, 2018.

[5] J. Samuels, E. Davies, D. Pope, et al., Collecting DNA from arrestees: implementation lessons, NIJ J (2012) 18—25.

[6] J.E. Samuels, E.H. Davies, D.B. Pope, Collecting DNA at Arrest: Policies, Practices, and Implications, Final Technical Report, Urban Institute, Washington, 2013, p. 79.

[7] H. Wallace, The UK national DNA database: balancing crime detection, human rights and privacy, EMBO Rep. 7 (2006). S26—S30.

[8] C. McCartney, The DNA expansion programme and criminal investigation, Br. J. Criminol. 46 (2006) 175—192.

[9] J. Butler, Advanced Topics in Forensic DNA Typing: Methodology, Elsevier, London, 2012.

[10] The Law Dictionary, What is effectiveness? definition of effectiveness (Black's Law Dictionary) [Internet]. Law Dict. 2012 [cited 2017 Apr 8], Available from: http://thelawdictionary.org/effectiveness/.

[11] The Law Dictionary, What is efficiency? definition of efficiency (Black's Law Dictionary) [Internet]. Law Dict. 2012 [cited 2017 Apr 9], Available from: http://thelawdictionary.org/efficiency/.

[12] K. van der Beek, Measuring the Effectiveness and Efficiency of Forensic DNA-Databases, Promega Corporation, Grapevine, TX, 2015 [cited 2017 Apr 9]. Available from: https://www.promega.com/-/media/files/products-and-services/genetic-identity/ishi-26-oral-abstracts/9-van-der-beek.pdf.

[13] FGPI, Establishing Best Practice for Forensic DNA Databases [Internet]. Forensic Genetics Policy Initiative, 2017 [cited 2017 Oct 3]. Available from: http://dnapolicyinitiative.org/wp-content/uploads/2017/08/BestPractice-Report-plus-cover-final.pdf.

[14] C. McCartney, A.O. Amankwaa, DNA Databases: It's Still Far from Clear How Effective They Are in Fighting Crime [Internet]. The Conversation, 2017 [cited 2018 Apr 18]. Available from: http://theconversation.com/dna-databases-its-still-far-from-clear-how-effective-they-are-in-fighting-crime-85137.

[15] A.O. Amankwaa, C. McCartney, The UK National DNA database: implementation of the protection of freedoms act 2012, Forensic Sci. Int. 284 (2018) 117—128.

[16] v S and Marper, The United Kingdom [Internet]. 2008 [cited 2016 Mar 11], Available from: http://www.bailii.org/eu/cases/ECHR/2008/1581.html.

[17] C. McCartney, Of weighty reasons and indiscriminate blankets: the retention of DNA for forensic purposes, Howard J. Crim. Justice 51 (2012) 245—260.

[18] B. Blakemore, C. Blake, Can the national DNA database be effective and comply with human rights legislation? Police J. 85 (2012) 191—202.

[19] A.J. Jeffreys, V. Wilson, S.L. Thein, Individual-specific "fingerprints" of human DNA, Nature 316 (1985) 76—79.

[20] P. Gill, A.J. Jeffreys, D.J. Werrett, Forensic application of DNA 'fingerprints.', Nature 318 (1985) 577—579.

[21] A.J. Jeffreys, J.F.Y. Brookfield, R. Semeonoff, Positive identification of an immigration test-case using human DNA fingerprints, Nature 317 (1985) 818—819.

[22] J.D. Aronson, DNA fingerprinting on trial: The dramatic early history of a new forensic technique, Endeavour 29 (2005) 126—131.

[23] Criminal justice and public order act [Internet]. Sect. 54-58 1994, Available from: http://www.legislation.gov.uk/ukpga/1994/33/contents.

[24] R v Weir [Internet], [cited 2016 Oct 9], 2000. Available from: http://www.bailii.org/ew/cases/EWCA/Crim/2000/43.html.

[25] Attorney general's reference No. 3 of 1999 [Internet]. 2000 [cited 2017 Mar 16], Available from: http://www.bailii.org/uk/cases/UKHL/2000/71.html.

[26] Nuffield Council on Bioethics, The Forensic Use of Bioinformation: Ethical Issues. London, 2007.

[27] Criminal justice and police act [Internet]. Sect. 82 2001, Available from: http://www.legislation.gov.uk/ukpga/2001/16/contents.

[28] Criminal justice act [Internet]. Sect. 10 2003, Available from: http://www.legislation.gov.uk/ukpga/2003/44/contents.

[29] National DNA Database Ethics Group, Annual Report of the Ethics Group: National DNA Database 2008, National DNA Database Ethics Group, London, 2008.

[30] R. Williams, P. Johnson, Inclusiveness, effectiveness and intrusiveness: issues in the developing uses of DNA profiling in support of criminal investigations, J. Law Med. Ethics 33 (2005) 545–558.

[31] Human Genetics Commission, Public Attitudes to Human Genetic Information, Human Genetics Commission, London, 2001.

[32] J. Burrows, R. Tarling, Measuring the impact of forensic science in detecting burglary and autocrime offences, Sci. Justice 44 (2004) 217–222.

[33] R. Williams, P. Johnson, "Wonderment and dread": representations of DNA in ethical disputes about forensic DNA databases, New Genet. Soc. 23 (2004) 205–223.

[34] C. McCartney, Forensic Identification and Criminal Justice: Forensic Science, Justice and Risk, Willan Publishing, Cullompton, 2006.

[35] HGC, Citizens' Inquiry into the Forensic Use of DNA and the National DNA Database: Citizens' Report, Human Genetics Commission, London, 2008.

[36] National DNA Database Board, National DNA Database: Annual Report, 2003 to 2004, Forensic Science Service, Birmingham, 2004.

[37] National DNA Database Strategy Board, National DNA Database: Annual Report, 2007 to 2009, NDNAD Strategy Board, London, 2012.

[38] National DNA Database Strategy Board, National DNA Database: Annual Report, 2006 to 2007, NDNAD Strategy Board, London, 2012.

[39] National DNA Database Board, National DNA Database: Annual Report, 2004 to 2005, NDNAD Board, UK, 2006.

[40] D. Leary, K. Pease, DNA and the active criminal population, Crime Prev. Community Saf. 5 (2003) 7–12.

[41] v S and Marper, The United Kingdom [Internet]. 2008 [cited 2016 Mar 11], Available from: http://www.bailii.org/eu/cases/ECHR/2008/1581.html.

[42] R v Chief Constable of South Yorkshire Police (Respondent) ex parte LS (by his mother and litigation friend JB) (FC) (Appellant) and R v Chief Constable of South Yorkshire Police (Respondent) ex parte Marper (FC) (Appellant) [Internet]. 2004 [cited 2017 Mar 30], Available from: http://www.bailii.org/uk/cases/UKHL/2004/39.html.

[43] Protection of Freedoms Act [Internet], 2012. Available from: http://www.legislation.gov.uk/ukpga/2012/9/contents/enacted.

[44] M. Gabriel, C. Boland, C. Holt, Beyond the cold hit: measuring the impact of the national DNA data bank on public safety at the city and county level, J. Law Med. Ethics 38 (2010) 396–411.

[45] S.J. Walsh, J.M. Curran, J.S. Buckleton, Modeling forensic DNA database performance, J. Forensic Sci. 55 (2010) 1174–1183.

[46] ENFSI DNA Working Group, DNA Database Management Review and Recommendations, ENFSI, Wiesbaden, 2017.

[47] J.L. Doleac, The Effects of DNA Databases on Crime, Social Science Research Network, Rochester, NY, 2016. Report No.: ID 2556948.

[48] J.L. Doleac, How Do State Crime Policies Affect Other States? the Externalities of State DNA Database Laws, Social Science Research Network, Rochester, NY, 2016. Report No.: ID 2892046.

[49] J.K. Roman, S.E. Reid, A.J. Chalfin, et al., The DNA field experiment: a randomized trial of the cost-effectiveness of using DNA to solve property crimes, J. Exp. Criminol. 5 (2009) 345.

[50] F.R. Bieber, Turning base hits into earned runs: improving the effectiveness of forensic DNA Data bank programs, J. Law Med. Ethics 34 (2006) 222–233.

[51] A. MacGregor, Annual Report 2015: Commissioner for the Retention and Use of Biometric Material, Office of the Biometrics Commissioner, UK, 2016.

[52] C. McCartney, T.J. Wilson, R. Williams, The Future of Forensic Bioinformation, Nuffield Foundation, London, 2010.

[53] H. Wallace, A.R. Jackson, J. Gruber, et al., Forensic DNA databases–ethical and legal standards: A global review, Egypt. J. Forensic Sci. 4 (2014) 57–63.

[54] C.A. Visher, Incapacitation and crime control: Does a "Lock 'em up" strategy reduce crime? Justice Q 4 (1987) 513–543.

[55] A.R. Piquero, A. Blumstein, Does incapacitation reduce crime? J. Quant. Criminol. 23 (2007) 267–285.

[56] C. Stahlkopf, M. Males, D. Macallair, Testing incapacitation theory: youth crime and incarceration in California, Crime Delinq. 56 (2010) 253–268.

[57] S.N. Durlauf, D.S. Nagin, Imprisonment and crime, Criminol. Public Policy 10 (2011) 13–54.

[58] J.L. Doleac, R. Landersø, T. Anker, et al., The Effects of DNA Databases on the Deterrence and Detection of Offenders, Social Science Research Network, Rochester, NY, 2016. Report No.: ID 2811790.

[59] P. Wiles, Annual Report 2016: Commissioner for the Retention and Use of Biometric Material, Office of the Biometrics Commissioner, London, 2017.

[60] Office for National Statistics, Crime in England and Wales: Year Ending June 2017 [Internet], Office for National Statistics, London, 2017 [cited 2018 Aug 9]. Available from: https://www.ons.gov.uk/peoplepopulationandcommunity/crimeandjustice/bulletins/crimeinenglandandwales/june2017.

[61] A. Tseloni, K. Pease, DNA retention after arrest: balancing privacy interests and public protection, Eur. J. Criminol. 8 (2011) 32–47.

[62] A. Bhati, C.G. Roman, Evaluating and quantifying the specific deterrent effects of DNA Databases, Eval. Rev. 38 (2014) 68–93.

[63] D. Lazer, A.L. Caplan (Eds.), DNA and the Criminal Justice System: the Technology of Justice, MIT Press, Cambridge, Mass, 2004.

[64] C. McCartney, The DNA expansion programme and criminal investigation, Br. J. Criminol. 46 (2006) 175–192.

[65] R. Williams, P. Johnson, Genetic Policing: the Use of DNA in Criminal Investigations, Willan Publishing, Cullompton, 2008.

[66] S. Krimsky, T. Simoncelli, Genetic Justice: DNA Data Banks, Criminal Investigations, and Civil Liberties, Columbia University Press, New York, 2011.

[67] C. McCartney, Of weighty reasons and indiscriminate blankets: the retention of DNA for forensic purposes, Howard J. Crim. Justice 51 (2012) 245–260.

[68] N. Lynch, L. Campbell, The Collection and Retention of DNA from Suspects in New Zealand, Victoria University Press, Wellington, 2015.

[69] J. Lee, The presence and future of the use of DNA-Information and the protection of genetic informational privacy: A comparative perspective, Int. J. Law Crime Justice 44 (2016) 212–229.

[70] MPA Civil Liberties Panel, Protecting the Innocent: the London Experience of DNA and the National DNA Database [Internet], Metropolitan Police Authority, London, 2011 [cited 2017 Mar 29]. Available from: http://policeauthority.org/metropolitan/downloads/scrutinites/dna.pdf.

[71] FBI, CODIS - NDIS Statistics as of January 2019 [Internet]. Fed. Bur. Investig. 2019 [cited 2019 Mar 12], Available from: https://www.fbi.gov/services/laboratory/biometric-analysis/codis/ndis-statistics.

[72] Home Office, National DNA Database statistics: Q3 2018 to 2019 [Internet]. GOV.UK. 2019 [cited 2018 Dec 12], Available from: https://www.gov.uk/government/statistics/national-dna-database-statistics.

[73] FIND Strategy Board, National DNA Database: Annual Report, 2017 to 2018, Forensic Information Database Strategy Board, London, 2019.

[74] National DNA Database Strategy Board, National DNA Database: Annual Report, 2014 to 2015, National DNA Database Strategy Board, London, 2015.

[75] National DNA Database Strategy Board, National DNA Database: Annual Report, 2015 to 2016, National DNA Database Strategy Board, London, 2017.

[76] D. Taylor, B. Kokshoorn, A. Biedermann, Evaluation of forensic genetics findings given activity level propositions: A review, Forensic Sci. Int. Genet. 36 (2018) 34–49.

[77] R.A.H. van Oorschot, B. Szkuta, G.E. Meakin, et al., DNA transfer in forensic science: A review, Forensic Sci. Int. Genet. 38 (2019) 140–166.

[78] FIND Strategy Board, National DNA Database: Annual Report, 2016 to 2017, Forensic Information Database Strategy Board, London, 2018.

[79] R v FNC [Internet], [cited 2018 May 30], 2015. Available from: http://www.bailii.org/cgi-bin/format.cgi?doc=/ew/cases/EWCA/Crim/2015/1732.html&query=(bryon)+AND+(DNA).

[80] R v Tsekiri [Internet], [cited 2017 Mar 24], 2017. Available from: http://www.bailii.org/ew/cases/EWCA/Crim/2017/40.html.

[81] P.E. Tracy, V. Morgan, Big brother and his science kit: DNA databases for 21st century crime control criminology, J. Crim. Law Criminol. 90 (2000) 635–690.

[82] A.O. Amankwaa, Forensic DNA retention: public perspective studies in the United Kingdom and around the world, Sci. Justice 58 (2018) 455–464.

[83] M. Briody, T.D.N.A. Prenzler, Databases and property crime: a false promise? Aust. J. Forensic Sci. 37 (2005) 73–86.

[84] Carling MJ, Taylor R, Purser J, et al. The Contribution of Forensic Science to Murder and Other Serious Crime Investigation in England and Wales in 2009-10. London: National Policing Improvement Agency; Unpublished.

[85] A.A. Mapes, A.D. Kloosterman, CJ de Poot, DNA in the criminal justice system: the DNA success story in perspective, J. Forensic Sci. 60 (2015) 851–856.

[86] W. Wells, A.K. Fansher, B.A. Campbell, The results of CODIS-Hit investigations in a sample of cases with unsubmitted sexual assault kits, Crime Delinq. 65 (2019) 122–148.

[87] D.B. Wilson, D. McClure, D. Weisburd, Does forensic DNA help to solve crime? The benefit of sophisticated answers to naive questions, J. Contemp. Crim. Justice 26 (2010) 458–469.

[88] D.A. Schroeder, DNA and homicide clearance: what's really going on, J. Inst. Justice Int. Stud. 7 (2007) 276–295.

[89] F.R. Bieber, Turning base hits into earned runs: improving the effectiveness of forensic DNA data bank programs, J. Law Med. Ethics 34 (2006) 222–233.

[90] M. Briody, The effects of DNA evidence on sexual offence cases in court, Curr. Issues Crim. Justice 14 (2002) 159–181.

[91] M. Briody, The effects of DNA evidence on homicide cases in court, Aust. N. Z. J. Criminol. 37 (2004) 231–252.

[92] M. Briody, The effects of DNA evidence on property offences in court, Curr. Issues Crim. Justice 17 (2006) 380–396.

[93] ACIC, National criminal investigation DNA database [internet], Aust. Crim. Intell. Comm. (2018) [cited 2018 Dec 13]. Available from: https://www.acic.gov.au/our-services/biometric-matching/national-criminal-investigation-dna-database.

[94] T.P. Cross, M. Alderden, A. Wagner, et al., Biological Evidence in Adult and Adolescent Sexual Assault Cases: Timing and Relationship to Arrest, J. Interpers Violence (2017) 1–12.

[95] FBI, Rapid DNA [Internet]. Fed. Bur. Investig. 2017 [cited 2019 Mar 11], Available from: https://www.fbi.gov/services/laboratory/biometric-analysis/codis/rapid-dna.

[96] J. Buscaino, A. Barican, L. Farrales, et al., Evaluation of a rapid DNA process with the RapidHIT® ID system using a specialized cartridge for extracted and quantified human DNA, Forensic Sci. Int. Genet. 34 (2018) 116–127.

[97] D. Shackleton, J. Pagram, N. Andrews, et al., Development of enhanced sensitivity protocols on the RapidHITTM 200 with a view to processing

casework material. Sci. Justice [Internet]. 2019 [cited 2019 Mar 6], Available from: https://www.sciencedirect.com/science/article/pii/ S1355030618303289.

[98] J. Goulka, C. Matthies, E. Disley, et al., Toward a Comparison of DNA Profiling and Databases in the United States and England, RAND Corporation, Santa Monica, CA, 2010, p. 34.

[99] A.N. Groth, R.E. Longo, J.B. McFadin, Undetected Recidivism among Rapists and Child Molesters, Crime Delinq. 28 (1982) 450—458.

[100] S.J. Walsh, J.S. Buckleton, O. Ribaux, et al., Comparing the growth and effectiveness of forensic DNA databases, Forensic Sci. Int. Genet. Suppl. Ser. 1 (2008) 667—668.

[101] FBI, CODIS and NDIS Fact Sheet [Internet]. Fed. Bur. Investig. 2018 [cited 2018 Apr 25], Available from: https://www.fbi.gov/services/laboratory/ biometric-analysis/codis/codis-and-ndis-fact-sheet.

[102] ENFSI DNA Working Group, DNA Database Management Review and Rec- ommendations, ENFSI, 2016.

[103] ENFSI, ENFSI Survey on DNA Databases in Europe-June 2016 [Internet]. ENFSI. 2017 [cited 2017 Apr 11], Available from: http://enfsi.eu/wp-content/ uploads/2017/01/ENFSI-Survey-on-DNA-Databases-in-Europe-June-2016. pdf.

[104] F. Santos, H. Machado, S. Silva, Forensic DNA databases in European coun- tries: is size linked to performance? Life Sci. Soc. Policy. 9 (2013) 1—13.

[105] Thomson A. NDNAD Effectiveness Metrics. London: Home Office; Unpublished.;.

[106] National DNA Database Ethics Group, Annual Report of the Ethics Group: National DNA Database 2014, National DNA Database Ethics Group, London, 2015.

[107] J.L. Doleac, The Effects of DNA Databases on Crime [Internet], Social Science Research Network, Rochester, NY, 2016 [cited 2017 May 22]. Report No.: ID 2556948. Available from: https://papers.ssrn.com/abstract=2556948.

[108] J.L. Doleac, R. Landersø, T. Anker, et al., The Effects of DNA Databases on the Deterrence and Detection of Offenders [Internet], Social Science Research Network, Rochester, NY, 2016 [cited 2017 May 22]. Report No.: ID 2811790. Available from: https://papers.ssrn.com/abstract=2811790.

[109] J.L. Doleac, How Do State Crime Policies Affect Other States? the Externalities of State DNA Database Laws [Internet], Social Science Research Network, Rochester, NY, 2016 [cited 2017 Jan 11]. Report No.: ID 2892046. Available from: https://papers.ssrn.com/abstract=2892046.

[110] A. MacGregor, Annual Report 2014: Commissioner for the Retention and Use of Biometric Material, Office of the Biometrics Commissioner, London, 2014.