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Abstract: Different stakeholders use forensic DNA databases for different purposes; for example, law enforcement agencies use them as an investigative tool to identify suspects, and criminologists use them to study the offending patterns of unidentified suspects. A number of researchers have already studied their effectiveness, but none has performed an overview of the relevant literature. Such an overview could help future researchers and policymakers by evaluating their creation, use and expansion. Using a systematic review, this article synthesizes the most relevant research into the effectiveness of forensic DNA databases published between January 1985 and March 2018. We report the results of the selected studies and look deeper into the evidence by evaluating the relationship between the purpose, content, and effectiveness of DNA databases, three inseparable elements in this type of research. We classify the studies by purposes: (i) detection and clearance; (ii) deterrence; and (iii) criminological scientific knowledge. Each category uses different measurements to evaluate effectiveness. The majority of these studies report positive results, supporting the assumption that DNA databases are an effective tool for the police, society, and criminologists.

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The effectiveness of DNA databases in relation to their purpose and content: a systematic review

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ABSTRACT

Different stakeholders use forensic DNA databases for different purposes; for example, law enforcement agencies use them as an investigative tool to identify suspects, and criminologists use them to study the offending patterns of unidentified suspects. A number of researchers have already studied their effectiveness, but none has performed an overview of the relevant literature. Such an overview could help future researchers and policymakers by evaluating their creation, use and expansion. Using a systematic review, this article synthesizes the most relevant research into the effectiveness of forensic DNA databases published between January 1985 and March 2018. We report the results of the selected studies and look deeper into the evidence by evaluating the relationship between the purpose, content, and effectiveness of DNA databases, three inseparable elements in this type of research. We classify the studies by purposes: (i) detection and clearance; (ii) deterrence; and (iii) criminological scientific knowledge. Each category uses different measurements to evaluate effectiveness. The majority of these studies report positive results, supporting the assumption that DNA databases are an effective tool for the police, society, and criminologists.

Keywords: DNA database – systematic review – effectiveness – police investigation – criminological research

1 INTRODUCTION

The first national DNA database was created in the UK in 1995 (Wallace, 2006), and the use of DNA in police investigations has since become common practice (Bieber, 2006). Because of its unique character, DNA is believed to be a credible method of linking a suspect to a crime scene in order to solve crimes (Stappers et al., 2016). Links are made between sample profiles, which are DNA profiles preserved at crime scenes, and reference profiles taken from people who have been arrested (Jeuniaux et al., 2015). DNA analysis has become a routine investigative practice and forensic DNA databases have increased in size and number, and they have the potential to expand even further. More recently, criminologists have used DNA databases as a data source for their research, including work on criminal careers and geographical offending behavior (De Moor, Vander Beken, & Van Daele, 2017; Lammers, Bernasco, & van de Beek, 2011).

The use of DNA databases by police and criminologists is increasing, but their effectiveness is rarely considered. Perceptions of their success are mostly based on anecdotal evidence of individual cases in which DNA resulted in a suspect being identified. These individual successes have led some people to suggest they should be expanded in order to maximize their potential (Tracy & Morgan, 2000). However, despite the fact that DNA databases are widely believed to be useful, research into their effectiveness is necessary in order to scrutinize their existence, use, and possible expansion. This article fulfills that need by providing an overview of the most relevant research into the effectiveness of forensic DNA databases and synthesizing the results. This systematic review provides a clear picture of what has already been studied, and what remains the under-researched.

2 BACKGROUND: PURPOSE, CONTENT, AND EFFECTIVENESS

'Effectiveness' is the degree to which an identified purpose is achieved, and thus the relevance of an intervention. Ideally, the purpose of a forensic DNA database should be defined in national or state law. Their most common purpose is to identify suspects and solve crimes (Bieber, 2006). However, the potential of forensic DNA databases goes beyond this one purpose, which is solely focused on policing and prosecution. Therefore, the first objective of this systematic review is to identify other purposes for their use. Their effectiveness will be evaluated using different measurements, depending on their intended purpose. For example, if the purpose of a DNA database is to increase the number of suspects identified, its effectiveness can be measured by the degree to which a DNA profile matches a registered offender profile in the database (i.e. identification rate).

The evaluation of a database's effectiveness depends on its content, which, in turn, depends on its purpose. For example, assume that a database's purpose is to examine the criminal career of unidentified offenders. Because individual offenders usually commit different types of crimes (Leary & Pease, 2003), DNA profiles from different crime types must be included. The database's purpose may also influence another aspect of its content, namely the retention period of the DNA profiles. Taking the same example, in order to study criminal careers, profiles must be stored for a certain time period, which can be based on findings from scientific research.

Researchers generally focus on effectiveness as an isolated measure and do not explicitly clarify the impact on their research of the purpose and content of DNA databases. However, as has been explained above, there is an important relationship between a database's purpose, content, and

effectiveness. Therefore, as well as presenting a synthesis of the research findings this article also verifies the extent to which the researchers considered databases' purpose and content when evaluating their effectiveness. The triangular relationship of purpose—content—effectiveness serves as the theoretical framework of this article and its synthesis. It offers policymakers and researchers the opportunity to consider the existence, use, and possible expansion of forensic DNA databases.

3 METHOD

A systematic review is characterized by a transparent and structured search strategy that enables other researchers to replicate the entire literature search and inclusion of studies (Grant & Booth, 2009). In this section, we explain this literature search strategy in detail.

3.1 SEARCH STRATEGY

For this systematic review, potentially interesting databases were identified and searched using basic keywords (DNA, database, crime). If these first search results were in line with the eligibility criteria (see further), the database was included in the review and searched more thoroughly in the next phase. If not, the database was eliminated. Twelve databases (Appendix 1) were finally selected. In addition to these databases, we consulted the websites of international institutions that conduct research on the topic, and a first search of their studies was conducted in the same way as the databases. Four institutions—the European Network of Forensic Science Institutes, the UK Home Office, the Belgian National Institute for Criminalistics and Criminology, and the Dutch Wetenschappelijk Onderzoek- en Documentatiecentrum—were included, based on their relevance to the topic and the researchers' language proficiency (English and Dutch).

The following keywords and Boolean operators were used to search relevant articles: [DNA] AND [databa*] AND [effect* or effic* or result or evaluation or impact] NOT [chem* or biolog*]. Because this systematic research focuses on criminological studies we decided to adopt some safeguards in the keywords in order to avoid medical and biological studies. For example, we specified *crime* and *criminology* and excluded *biology* and *chemistry*. Despite the use of these inclusion and exclusion terms, a lot of medical or biological and other irrelevant articles still appeared in the search results, which explains the large number of articles that dropped out in the first phase of the selection. Later, we scanned the bibliographies of the selected studies to identify articles that had possibly been missed, which resulted in one extra study. After the search strategy was determined, the faculty librarian verified this protocol. No adjustments were necessary.

3.2 ELIGIBILITY CRITERIA

We identified several eligibility criteria that had to be met before the relevant studies were selected. Since the use of DNA as forensic evidence was first introduced in 1985 by Alec Jeffreys (Roman, Walsh, Lachman, & Yahner, 2012), we only selected articles published between January 1985 and March 2018 inclusive (when the literature search was terminated). We searched the international literature without geographical restrictions, but due to limitations in language proficiency only articles in English and Dutch were eligible for inclusion. As will be discussed later in this article, all included studies were conducted in Western Europe or the United States.

Only empirical studies were eligible for the systematic review, so opinion pieces, reviews, and evaluations of legislation were excluded. However, in order to offer a broad overview, no restrictions were placed on the method or study design. This resulted in the inclusion of a variety of studies, and makes it possible to present an encompassing and inclusive picture of the effectiveness of DNA databases. As mentioned in the introduction, effectiveness is a broad concept. Therefore, we included studies that evaluated databases' possible purposes and that used different measurements of effectiveness. We also included studies that examined the effectiveness of DNA testing in itself, since this (implicitly) acknowledges the existence of a DNA database in order to be able to compare DNA samples.

As a final criterion, the selected studies had to score at least 50% on the quality assessment. The quality assessment was based on the checklist of Kmet, Cook, and Lee (2004). This assesses the quality of quantitative studies by asking 14 questions that need to be evaluated using a score between 0 and 2, with 0 meaning applicable but not appropriate, 1 meaning appropriate but not sufficiently described and 2 meaning available and properly described. The checklist produces a percentage based on these scores. More than 68% [1–4, 7–11, 13–15, 17] of the studies scored above the relatively conservative threshold of 75%. Almost 32% of the studies [5, 6, 12, 16, 18, 19] scored between 50% and 75%, which is the more liberal threshold. In order to avoid bias caused by research that scored relatively low in the quality assessment, we decided to eliminate studies that scored less than 50%.

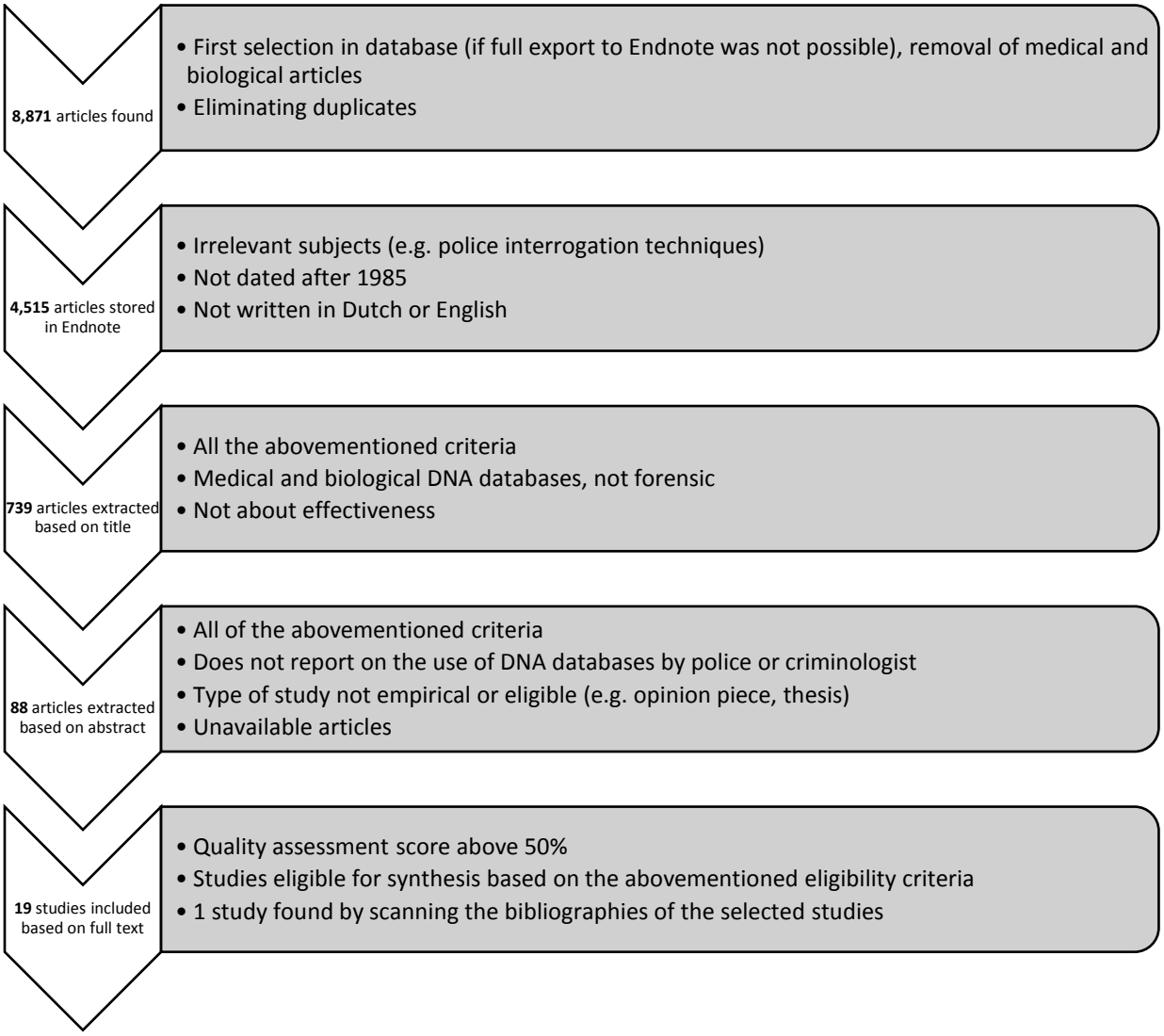
3.3 The selected studies

After eliminating duplicates, the search resulted in 8,871 articles, of which 4,515 were stored and managed in Endnote. Medical and biological articles had already been eliminated via the initial search conducted when browsing the databases. The selection procedure consisted of three stages. In the first stage we selected articles based on their title, which resulted in 739 articles. Next, we read the remaining studies' abstracts, and this resulted in 88 articles. Lastly, we read the full texts of these 88 articles, resulting in 18 studies meeting the eligibility criteria. After scanning the bibliographies of the selected studies, one more study was included. This study was not found in the database searches, but met the inclusion criteria. A summary of the 19 included studies is provided in Table 1, and a flow chart of the selection procedure and the criteria that were applied is shown in Figure 1.

3.4 Data extraction and synthesis

For each of the 19 studies we filled in a data extraction sheet that focused on their more general details, as well as the study design and key results (Appendix 2). We created a questionnaire (Appendix 3) that was thematically organized in order to compare and synthesize the individual studies' findings. As the goal of this systematic review is to offer an overview of the most relevant studies and their findings, and the study designs and methods used in the studies differ greatly, we decided to conduct a synthesis of the studies.

Figure 1. Flow chart of the selection procedure



4 SYNTHESIS OF RESULTS

This article aims to provide an overview of the most relevant literature on the effectiveness of DNA databases and key details of the researchers' findings. Therefore, this section includes a summary of each study. As mentioned earlier, the effectiveness of DNA databases is always measured against its particular purpose. We categorized the studies according to the databases' purpose, using three common categories for forensic DNA databases: (i) as a detection and clearance tool for police and prosecution; (ii) as a deterrence; and (iii) as a data source for criminological research. These categories were identified while reading into the topic, but were defined later based on the definitions used in the selected studies. We then organized the studies by the databases' intended purpose. In the summaries below, the studies are discussed based on the intended purpose of the database, measurement of effectiveness, study design, results, data source, and investigated crime types.

The included studies were mostly conducted in the United States (n = 6), the Netherlands (n = 5), the United Kingdom (n = 3), and Belgium (n = 3). Studies from Australia (n = 1) and Denmark (n = 1) were also eligible for this systematic review. All but four studies used data that was dated from before 2010. The crime types studied varied, but all were suitable for DNA extraction. Table 1 gives an overview of the purpose and main characteristics of the studies. In the synthesis, reference to the applicable study's ID is given in squared brackets.

4.1 DETECTION AND CLEARANCE

The first category to be considered is those studies that defined the purpose of databases as the detection or identification of suspects and clearance of crimes. The use of DNA databases by police and prosecution has grown in recent years (Bieber, 2006). Eight of the selected studies [6, 7, 12–16] focused on the detection and clearance effect of DNA databases. Across these studies, effectiveness was operationalized by four measurements that represent the different phases of the criminal justice system: (i) the identification rate; (ii) the arrest rate; (iii) the charge and prosecution rate; and (iv) the conviction rate.

First, the identification rate can be defined as the level of matches between DNA evidence found at the crime scene, and the profile of an identified individual registered in the DNA database during a police investigation that leads to the identification of the suspect. The majority of the selected studies used this measure to assess the effectiveness of the DNA database [6, 7, 12–14, 16]. Second, the arrest rate is the level of arrests made in police investigations as a result of DNA database searches [14, 15]. Compared to the identification rate, it is much more difficult to identify a direct link between a DNA database search and an arrest. Other police investigative tools may also have been used and this could have influenced the arrest rate. Third, we define the charge rate as the level of cases for which the police lay charges, whereas we define the prosecution rate as the level of cases that are sent to court [6, 14]. The influence of other evidence that leads to the charge or prosecution must be taken into account when using this measurement for effectiveness, for the same reason as the arrest rate. Forth, the conviction rate is the level of charges that are proven in court [6]. Here, the decision of the judge could be influenced by factors other than DNA evidence. Some of the included studies evaluate effectiveness based on more than one of these measurements, and we would expect this to improve the reliability of their results.

Leary and Pease (2003) [12] examined criminal careers by analyzing data from the UK National DNA database over a 19-month period. Their results showed that although the number of submissions increased, the proportion of matches with profiles already in the DNA database stagnated at 58% (i.e. identification rate). According to the authors, these results can be explained by a rapidly changing criminal population: the offenders who are included in the DNA database no longer commit crimes, whereas active criminals are not yet recorded in the DNA database. To conclude, Leary and Pease stressed "the importance of the liberal taking of criminal justice samples (i.e. DNA samples) at the first opportunity, regardless of the crime committed or alleged" (p. 11). Mapes, Kloosterman, and de Poot (2015) [13] examined the number of times DNA taken from a crime scene resulted in the identification of an as yet unknown suspect (referred to as a 'cold hit') for serious and high-volume crimes. For this, they analyzed 243 Dutch criminal case files where at least one DNA trace was secured and analyzed. They found that DNA extracted from crime scenes led to a cold hit in 3% of the serious crime cases and 1% of the high-volume crimes. Roman, Reid, Chalfin, and Knight (2009) [14] conducted a randomized controlled trial in which they explored the added value of DNA analysis for property crimes. They randomly assigned cases to a treatment group, where DNA traces were analyzed after collection, and a control group, where DNA traces were collected but not analyzed. Their hypothesis, that processing DNA evidence from high-volume crime scenes would result in more identifications and arrests of suspects, was confirmed by their results. A suspect was identified in 31% of the treatment group cases, which is more than twice as many cases as in the control group (12.8%). There was an arrest in 21.9% of the treatment group cases, compared to only 8.1% in the control group, and more than twice as many treatment group cases were accepted for prosecution than control cases. Taverne, Nijboer, Abdoel, and Farooq (2013) [16] investigated the effectiveness of the Dutch Legal Act 'DNA-Convicted Offenders' (in Dutch: Wet DNA-Veroordeelden) in relation to the detection, prosecution, and charging of offenders. They analyzed information gathered from the prosecutor's office and the Dutch DNA database for serious offenses and high-volume crimes. Taverne et al. reported that, in 2011, 67% of the convicted offenders had their DNA recorded in the DNA database after their conviction, and in 7.3% of the cases analyzed between 2005 and 2012 a match could be made with a DNA profile found on a crime scene.

Other studies are more nuanced and narrow the power of DNA databases. Dunsmuir, Tran, and Weatherburn (2008) [6] used police and court statistics to evaluate the effect of an expanding DNA database in New South Wales (Australia) on clearance rates for violence and high-volume crimes from 1995 to 2007. From 2001, New South Wales began collecting and storing the DNA of all prisoners, which resulted in an expansion of the DNA database. By using a time-series analysis, the authors examined whether this expansion had a positive influence on the charge and conviction rates. The study concluded that the results depend strongly on the crime type, but an overall positive and significant effect on the clearance and charge rates was reported. The expansion of the DNA database was found to have increased its effectiveness on a broad scale, although significant negative effects were found regarding the conviction rates, and no explanation was given. Although, Dunsmuir et al. take into account some other historical events for these current results, such as the implementation of other police investigative tools, no analyses were made in order to confirm or reject this hypothesis. House, Cullen, Snook, and Noble (2006) [7] examined the effectiveness of the Canadian national DNA database by analyzing the convictions of 106 individuals guilty of sexual murderer and 85 guilty of sexual assault that had occurred prior to the formation of the database, to assessed whether these earlier convictions would have been suitable for recording in the DNA

database. Their idea was that if these criminals had already been registered in the DNA database, they would have been identified more easily. The results showed that 61% of the murderers and 72% of the sexual offenders had a prior conviction, but only a minority of these offenders would have been included in the DNA database. House et al. stress the importance of expanding the Canadian national DNA database in order to maximize its effectiveness. Schroeder (2007) [15] examined the possible effect of DNA evidence on homicide clearance rates and its role in case closure based on the arrest rate. For this quasi-experimental design he categorized 602 homicide cases into groups based on the role DNA played in the investigation, being "victim only DNA," "direct link between a tested suspect and evidence from the crime scene," "database could provide further lead," and "insufficient DNA for analysis." There were only 40 cases where DNA evidence was available prior to arrest and was actually used during the police investigation. Conversely with the hypothesis, Schroeder found that the case clearance rate was much higher in cases where the available DNA was not used (74%) compared to the cases where the DNA evidence was used (27.5%). When removing cases in which a suspect was found immediately after the crime (for which he expects that DNA would be less important in identifying the suspect), the percentage of cases that had a DNA analysis available pre-arrest increased from 6.7% to 9.3%. He stated that the implementation of a large DNA database would have a minimal influence on the homicide clearance rates.

After synthesizing the applicable selected studies, it is clear that the conclusions are generally in favor of the use of DNA databases by police and prosecution. The ability of DNA to detect offenders and clear crimes is confirmed by most studies. However, this conclusion may need to be nuanced for three reasons. First, effectiveness is operationalized in different ways. This makes it difficult to compare the different study results. Second, this review indicates that the effectiveness of DNA databases may vary according to the crime type. It is of the utmost importance that police and prosecutors remain aware of the possible weaknesses of DNA databases. Third, these studies only took the effectiveness of DNA databases into account. Thus, the impact of other frequently used research methods, such as witness statements, could not be assessed.

4.2 Deterrence

The second category to be considered is those studies that defined the purpose of databases as a deterrence, which refers to their potential to prevent future crimes, both at an individual (i.e. offenders recorded in the DNA database are less likely to commit future crimes) and aggregate level (i.e. reducing general crime rates) (Bhati, 2010). As this purpose focuses on the prevention of crime, we can say that it measures how effective DNA databases are in keeping society safe. Four of the included studies [1, 4, 5, 17] examined the deterrence effect of DNA databases and evaluated their effectiveness based on two different measurements: the recidivism rate and the crime rate. The recidivism rate focuses on the specific or individual deterrence effect (i.e. discouraging an individual from committing future crimes), which can be calculated by using re-arrest and re-conviction rates. Re-arrest refers to the probability of a new arrest, and re-conviction to and a new conviction, following DNA registration in the DNA database. The crime rate refers to the general or aggregate deterrence effect (i.e. prevention of crime in society by discouraging people from committing future crimes).

Bhati (2010) [1] analyzed the re-offending patterns of released prisoners in Florida between 1996 and 2004 in order to investigate the specific deterrence effect of the DNA database. He examined the

hypothesis that the knowledge that they are recorded in the DNA database deters offenders from future crimes because the probability of detection and punishment increases. The treatment group of the quasi-experimental design consisted of all released prisoners whose DNA was stored in the DNA database prior to their release. The control group, on the other hand, consisted of released prisoners whose DNA was not included in the database prior to their release. Bhati found that there is evidence for the specific deterrence effect of DNA databases, especially for robbery and burglary, which means that being registered in the DNA database hinders future offending behavior. At the same time, for some crime types (i.e. violent crimes) the results showed a negative effect of being included in the DNA database.

Doleac (2016) [4] explored both the individual and aggregate deterrence effect of DNA databases on criminal behavior and crime rates. The individual deterrence effect is measured by comparing the recidivism rates of offenders released before and after the expansion of DNA laws in seven different US states between 2000 and 2010. It is important to note that the author did not observe actual DNA collection from the offenders prior to release; there was only a theoretical requirement to submit a DNA sample based on criminal history and the DNA law. Doleac found that, among the offenders released after the database's expansion, recidivism was reduced by 17% (statistically significant) for serious violent offense cases and 6% (marginally significant) for serious property offense cases. The aggregate deterrence effect of DNA databases was evaluated by analyzing annual state-level data on DNA database size and crime rates between 2000 and 2010 for the same seven states. The results show that violent crimes decreased by 45% and property crimes by 35% following the expansion of the DNA databases, both statistically significant figures. In a later study, however, Doleac (2017) [5] reported an increase in violent and property crime rates in one state when another state adds an offender profile to their own database, and the proximity of states has an influence on the effect size. This observation leads her to conclude that DNA database expansion can cause crime displacement, as offenders are likely to move to other places as a response to changing state policies in order to avoid arrest.

Tegner Anker, Doleac, and Landerso (2017) [17] studied the influence of the Danish DNA database on the specific deterrence and detection of offenders by comparing the recidivism rates of offenders charged after reforms in 2005 (when, due to the expansion of the law, these offenders had a greater chance of being added to the DNA database) and offenders charged before the reform, for a variety of crimes (e.g. violent crimes, sexual offenses, property offenses). The authors found that the probability of a new conviction decreased by 42%, and the probability of recidivism (i.e. committing a new crime) reduced by 43%, in the first year after the reform. The effects were the strongest for violent crimes, with a reduction of 48%. They found that the probability of detection (i.e. identification of the suspect) increased by 3–4% due to DNA profiling, which supports the positive results above (Section 4.1).

The findings of these studies suggest that DNA databases have a significant crime-reducing effect on both an individual and an aggregate level. Thus, including offenders in a DNA database does decrease the probability of future crimes. However, some caution is needed. First, although the results suggest a positive effect for own-area crime rates, possible perverse effects must be taken into account, such as the displacement of crime to another area. Policymakers should be aware of these possible consequences and take them into account when evaluating the creation, use, and possible expansion of their national or regional DNA database. Second, this review indicates that the deterrence effect

of DNA databases may vary according to the crime type. Third, other elements that may have an impact on recidivism (e.g., policy and prevention measures) were not taken into account in the research. These last two elements also apply to studies that explored DNA databases as a detection and clearance tool.

4.3 Criminological knowledge

The third category to be considered is those studies that defined the purpose of DNA databases as a data source of criminological knowledge and referred to their use by criminologists. The main idea here is that DNA databases resolve some limitations of other criminological data sources (Lammers et al., 2011). For example, it has been said that police-recorded crime data only include identified offenders and do not contain information about offenders who have never been arrested or identified (i.e. unknown offenders) (De Moor et al., 2017). However, it is important to study unknown offenders, as research suggests that offenders who are not arrested have different features from those who are (Lammers, 2013). DNA databases are currently used by a limited group of criminologists, who mainly examine criminal networks, criminal careers and the spatial behavior of unknown offenders. Eight of the included studies [2, 3, 8–11, 18, 19] used DNA databases as an alternative data source for their criminological research and evaluated their effectiveness by comparing the outcomes with the (expected) outcomes of police-recorded crime databases.

For this systematic review, two recent studies by De Moor, Vandeviver, and Vander Beken were selected. In the first study, De Moor, Vandeviver, and Vander Beken (2018) [2] considered whether DNA databases are a valid source when studying the spatial behavior of unknown offenders. Therefore, they compared the spatial distribution of unsolved crimes stored in the Belgian police-recorded crime data with the spatial distribution of unsolved crimes stored in the Belgian DNA database, for four crime types (violent theft, aggravated burglary, lethal violence, and sexual offenses). The findings suggest that the DNA database is representative of the police-recorded crime data, although the added value of DNA databases lies in combining them with police databases. This is addressed in the second study, in which De Moor et al. (2018) [3] combined the Belgian police-recorded crime database and the DNA database to evaluate the added value of DNA data in the study of serial co-offending behavior. They found that combining the two databases revealed more and larger networks of crimes, and that the spatiotemporal spread of the crime networks was larger, than when the police database alone was used.

Jeuniaux, Duboccage, Renard, Van Renterghem, and Vanvooren (2016) [8] explored the possibilities of DNA databases as a tool to link crime scenes irrespective of whether the offender could be identified or not. By using the Belgian DNA database, Jeuniaux et al. discovered more than 400 criminal networks that differed in size, crime types, and geographical locations. The findings of this study could be of great value to the police, but also in criminological research, as they increase knowledge about criminal behavior and criminal networks. By using DNA databases, researchers create a more realistic and comprehensive view that does not limit the knowledge to known offenders and their behavior or to networks of known offenders.

Three studies by Lammers et al. were included in this systematic review. Lammers, Bernasco, and Elffers (2012) [9] used data from the Dutch DNA database to examine whether the seriousness of previous crimes, the amount of previous crimes, and possible specialization in crime type affected the probability of arrest by comparing two or more crimes where the same DNA profile was found at

the crime scene of identified and unidentified offenders[1] in violent crime cases, sexual offense cases, and high-volume crime cases. According to Lammers et al., 35% of offenders who leave their DNA at the crime scene will not be arrested within eight years. The results showed that the abovementioned characteristics do have an influence on the probability of arrest: for every extra crime committed, the probability of arrest increased by 19%, and complete versatility in crime type increased the probability of arrest by 184%. Only the seriousness of the offenses did not have a significant influence on the probability of arrest. In their second study, Lammers and Bernasco (2013) [10] used DNA data to compare the crime series of identified offenders with that of unidentified offenders in order to study the influence of geographical dispersion of the crime locations of serial offenders on the probability of arrest. The results showed that an increase in the number of police regions in which the offender commits crimes resulted in a 9% decreased probability of arrest. Further, when the offender committed their crime in another police region than the previous crime, the probability of arrest decreased by 13%. Last, for every extra border the offender crossed to commit their next crime, the probability of arrest decreased by 7%. In the third study, Lammers (2014) [11] compared the spatial offending patterns of arrested and non-arrested offenders based on the mean inter-crime distance (MICD) of the locations where the offenders committed their crimes. The hypothesis of this study was that "if offenders with a small MICD have a greater probability of being arrested, they will be overrepresented in police arrest data, and results of studies based on these data will then probably be biased with respect to the MICD" (p. 147). She examined the MICD of serial offenders stored in the Dutch DNA database, which she defined as offenders who had committed at least two crimes classed as violent crimes, sex offenses, or high-volume crimes. Lammers found that most offenders had a short MICD, and the difference between arrested and non-arrested offenders was small. This suggests that MICD does not influence the probability of arrest, and that the selectivity of arrest data concerning the spatial behavior of serial offenders may not be justified, which is in contrast with the results of her previous studies. This difference can be explained by the different scales used by Lammers and Bernasco (2013) [10] and Lammers (2014) [11]. Lammers stated that although offenders commit crimes in different regions, as reported in the study of 2013, the MICD can still differ.

Townsley, Smith, and Pease (2006) [18] used DNA samples to investigate offender specialization and its policing implications. Their preference for DNA data arose from its ability to include unknown offenders and because it enables them to explore the criminal career of offenders who tend to escape arrest. Their results support earlier research into criminal careers, suggesting they are relatively short (a maximum of three years) and varied. Townsley et al. found that taking DNA samples from thieves and drug offenders was more valuable than taking samples from prior violent or sexual offenses in providing evidence for later serious violent and sexual offenses. Their conclusions supported the view that DNA samples should be taken as early and widely as possible. As such, Townsley et al. also provided valuable insights in terms of detection and clearance of crimes. Wiles and Costello (2000) [19] used both police-recorded crime data and DNA data to examine offender travel patterns in volume crime cases. The UK's National DNA Database was used to investigate patterns of offenders who were unknown to the police. Based on the DNA data, the authors concluded that the travel patterns of unknown offenders did not significantly differ from those of known offenders. Travel distances were relatively short, so that volume crimes were a relatively localized phenomenon.

[1] De Moor et al. (2018a, 2018b) used the term unknown offenders, but both authors target the same group offenders, being offenders that are individualized by their DNA found on the crime scenes, but their identity ~~stays~~ remains unknown.

The results of the studies included in this synthesis support the use of DNA databases as a new data source for criminological research. However, some authors reported no difference between the results of the DNA data and the police-recorded crime data. These authors explained the use of the DNA database to study offenders, irrespective of whether they are known to the police or not. The results of prior studies open the door for criminologists to consider DNA databases as a new and additional data source in order to enrich their research and knowledge about criminal behavior.

Table 1. Overview of the included studies' purpose and main characteristics

Study ID	Study	Country	Period of used data	Studied crime types	Design	Purpose and *measurement*	Findings
1	Bhati (2010)	USA	1996–2004	Robbery, burglary, property crimes, violent crimes and drug-related crimes	Quasi-experimental design comparing released offenders whose DNA is in the database with released offenders whose DNA is not in the DNA database	Deterrence: *Recidivism rate*	DNA databases are an effective deterrence and detection tool
2	De Moor et al. (2018)	Belgium	2014	Violent theft, aggravated burglary, lethal violence and sexual offenses	Quasi-experimental design comparing the DNA database and the police-recorded crime database	Criminological knowledge: *Criminal career*	DNA databases are more effective in studying the crimes committed by unidentified offenders than other criminological data sources
3	De Moor et al. (2018)	Belgium	2014	Violent theft, aggravated burglary, lethal violence and sexual offenses	Quasi-experimental design comparing a combined dataset with the police-recorded crime database	Criminological knowledge: *Spatial behavior*	Combining the DNA database and the police-recorded crime database gives a more complete view on criminal networks than the police database alone
4	Doleac (2016)	USA	2000–2010	Violent and property crimes	Quasi-experimental design comparing released offenders post-expansion of the DNA database and released offenders pre-expansion of the DNA database	Deterrence: *Recidivism rate*	DNA databases do have a deterrence effect on convicted offenders for violent and property crimes
5	Doleac (2017)	USA	2000–2014	All crimes	Quasi-experimental design comparing own-state crime rates and DNA database policies and other-state crime rates and DNA database policies	Deterrence: C*rime rate*	Expanding the own-state DNA database results in increased crime rates in nearby states
6	Dunsmuir et al. (2008)	Australia	1995–2007	Assault, sexual assault, break and enter, robbery, motor vehicle theft and stealing from motor vehicles	Time series	Detection and clearance: *Identification, charge and prosecution, conviction rate*	DNA databases do result in more cleared cases, but also result in fewer convictions. The results strongly depend on the crime type
7	House et al. (2006)	Canada	Unknown	Sexual murder and sexual assault	Descriptive design	Detection and clearance: *Identification rate*	DNA databases are not used to their full potential as they can only identify offenders whose DNA is already included, so the identification rate remains low
8	Jeuniaux et al. (2016)	Belgium	2014	Burglary, robbery, unknown, crime group, murder and miscellaneous	Descriptive design	Criminological knowledge: *Criminal career*	DNA databases offer more opportunities than only identifying offenders, they also offer insight in criminal networks
9	Lammers et al. (2012)	The Netherlands	2002-2009	Violent crimes, sex offenses, burglary, theft and theft of or from a car	Quasi-experimental design comparing crime series of unidentified offenders (DNA available in DNA database) and crime series of identified offenders	Criminological knowledge: *Criminal career*	DNA databases are unique data sources for criminological research when studying unidentified offenders
10	Lammers and Bernasco (2013)	The Netherlands	2002–2009	Violent crimes, sex offenses, burglary and	Quasi-experimental design comparing crime series of unidentified offenders	Criminological knowledge: *Spatial behavior*	DNA databases are unique data sources for criminological research

				high-volume crimes	(DNA available in DNA database) and crime series of identified offenders		when studying unidentified offenders
11	Lammers (2014)	The Netherlands	2002–2009	Violent crimes, sex offenses, burglary and high-volume crimes	Quasi-experimental design comparing crime series of unidentified offenders (DNA available in DNA database) and crime series of identified offenders	Criminological knowledge: *Spatial behavior*	DNA traces offer reliable links between (unidentified) offenders and crime scenes. Arrest data seem less selective than assumed, as DNA data result in the same conclusions
12	Leary and Pease (2003)	UK	2000–2001	Unknown	Descriptive design	Detection and clearance: *Identification rate*	The effectiveness of DNA databases is not necessarily linked with its size, but more with the proportion of those recently included in the database
13	Mapes et al. (2015)	The Netherlands	2011	Serious crimes (armed robbery, sexual assault, etc.) and high-volume crimes	Descriptive design	Detection and clearance: *Identification rate*	DNA databases are effective in the identification of suspects
14	Roman et al. (2009)	USA	2005–2007	Residential and commercial burglary	Experimental design, randomly assign property crime cases to the treatment group (collecting and analyzing DNA traces) and the control group (collecting, but not analyzing DNA traces)	Detection and clearance: *Identification, arrest, charge and prosecution rate*	DNA databases do increase the probability of identification, arrest and prosecution in cases of property crimes
15	Schroeder (2007)	USA	1996–2003	Homicide	Quasi-experimental design comparing homicide cases with DNA analyzed and used before making an arrest and homicide cases without DNA evidence	Detection and clearance: *Arrest rate*	DNA databases do not increase the probability of clearance in homicide cases
16	Taverne et al. (2013)	The Netherlands	2005–2012	High-volume crimes and serious offenses	Descriptive design	Detection and clearance: *Identification rate*	DNA databases do increase the probability of identification of an offender
17	Tegner Anker et al. (2017)	Denmark	2003–2007	Violent crimes, property crimes, sex offenses, other penal offenses (drugs, etc.) and violations of the Weapon Act	Quasi-experimental design comparing offenders convicted after the DNA database expansion and offenders convicted before the DNA database expansion of 2005	Deterrence: *Recidivism rate*	DNA databases increase the probability of detection and have a deterrence effect on future crime
18	Townsley et al. (2006)	UK	2003	Violent crimes, sexual offenses, robbery, theft and drug offenses	Descriptive design	Detection and clearance: *Criminal career*	DNA databases offer an interesting data source for criminological research as they include unidentified offenders
19	Wiles and Costello (2000)	UK	1997	Volume crimes	Descriptive design	Criminological knowledge: *Spatial behavior*	The results of DNA databases confirm the results of police-recorded crime data when investigating the travel patterns of unidentified offenders

5 Discussion

In this last part of the article, we discuss the findings of the systematic review and make the link between the purpose, content, and effectiveness of DNA databases. We also discuss the limitations of the current study and directions for further research.

5.1 Effectiveness in relation to purpose and content

As mentioned at the start of this article, a triangular relationship exists between the purpose, content, and effectiveness of forensic DNA databases to which little attention was paid in the selected studies. None of the studies explicitly mention the influential relationship between these three aspects. Most researchers mentioned the purpose and the measurement for effectiveness, but they seldom paid attention to the content of the DNA database. Only Bhati [1] included an overview of the crime types that were eligible for inclusion in the DNA database he studied. Other authors either mentioned content briefly as a marginal issue, or did not mention it at all. This makes it difficult to compare the selected studies, as the inclusion criteria and retention policies of forensic DNA databases vary due to discrepancies in legislation. International variations in factors such as crime types, categories of offenders (convicted versus arrested offenders), and retention period are responsible for differences in results.

It is notable that the majority of the recommendations made in the included studies [1, 5, 8, 13–17, 19] concern the possible expansion of DNA databases in terms of the amount of profiles recorded and the inclusion criteria. None of the studies explicitly rejected the expansion of DNA databases. However, the researchers did not always support the expansion of DNA databases as a tool for tackling crime. Some were skeptical about the benefits of expansion. Schroeder (2007) [15] reported that an expansion of the DNA database could help to solve homicide cases, although he remarked that the ultimate effect would only be marginal. According to other authors, such as Bhati (2010) [1], House et al. (2006) [7], Leary and Pease (2003) [12] and Mapes et al. (2015) [13], the expansion of DNA databases would only have positive effects on detection and clearance if the offender were already included in the database. For that reason, they called for DNA sample-taking at the earliest opportunity, as these samples are necessary to ensure a match with more serious offenses. Furthermore, a number of authors stated that the list of crime types that are eligible for inclusion must be enlarged [1, 8, 15].

However, caution is required. Should we only include the profiles of those convicted of the most serious offenses, or do we include the profiles of everyone who is ever arrested? Do we expand the list of crime types that are eligible for DNA sampling, such as drug offenses and other minor offenses? Or, ultimately, do we create a national DNA database containing the profiles of all citizens, offender or not? Tracy and Morgan (2000) identified seven possible scenarios for the use of DNA databases, ranging from no DNA database at all, through the inclusion of all convicted offenders, to a national DNA database of the entire population. They noted a so-called *expansionist tendency* in the regulation of and tolerance towards DNA databases. In relation to this finding, Dahl and Sætnan (2009) argued that the legal restrictions concerning the inclusion criteria for DNA samples have softened, and increasing numbers of crimes and individuals are being recorded in databases. Ethical issues such as privacy, proportionality, and function creep must be taken into account, along with the costs and possible backlogs that would result from large amounts of samples that need to be tested (Bieber, 2006).

Furthermore, it is clear that effectiveness is measured differently depending on the study. For example, Leary and Pease (2003) [12] calculated the identification rate as 58%. In contrast, Mapes et al. (2015) [13] found an identification rate of 1 to 3%, depending on the crime type. An explanation for this difference can be found in the definition of identification rate. Leary and Pease measured

cold hits, by which they mean the matches between a forensic profile found at the crime scene and a reference profile of a suspect, independent of the results of other investigative tools. In contrast, Mapes et al. only measured the identifications that were exclusively made by a match with the DNA database. In other words, if a suspect had already been identified by other investigative practices and the DNA database found a match, this match was not included in the results. This observation points out the necessity of standard definitions and thresholds when calculating the effectiveness of DNA databases.

5.2 Study limitations

It is important to recognize the possibility of different forms of biases, such as selection bias and publication bias, which are common concerns when conducting a systematic review and have an influence on validity (Rothstein, Sutton, & Borenstein, 2005). Publication bias can be defined as the systematic difference between published and unpublished studies concerning the nature and direction of the results (Song, Hooper, & Loke, 2013). According to Dwan et al. (2008), there is strong evidence of an association between the significance of the results and the publication of the study. More specifically, it is more likely that a study that reports positive and significant results will be published than a study that reports negative or null results (Franco, Malhorta, & Simonovits, 2014). For this systematic review, all studies have been peer reviewed and some included studies reported negative results, so we can assume that publication bias will be limited. Furthermore, we also consulted the websites of four relevant institutions, which broadens the foundations on which the results are based.

Selection bias must be taken into account as well. For this research, the selection of studies and the analysis and synthesis were done by a single researcher, with a second researcher discussing the work as it progressed. The faculty librarian was asked to evaluate the search strategy and process and approved the written proposal. We used this approach in an attempt to limit the probability of selection bias when searching for eligible studies.

As mentioned in the methods section, only articles in English and Dutch were eligible for inclusion due to limitations in language proficiency. This may have had an impact on the included studies. However, the impact of this limitation should not be exaggerated as English is a common language in scientific research, even for non-native English speakers.

One last issue that needs to be taken into account is the difficulty in comparing and generalizing the results of this study. The studies varied in data source and perspective (operational use, criminological use of DNA databases). Additionally, methodological differences between the studies (see Table 1) made it difficult to perform a meta-analysis and a funnel plot. Therefore, the presented outcomes and remarks must be viewed with caution and considered in context.

5.3 Directions for further research

This systematic review has stressed the importance of the triangular relationship between the purpose, content, and effectiveness of forensic DNA databases. We have observed that the selected studies did not thoroughly explore and report this relationship, which made it difficult to compare them. Future researchers in this area must keep this relationship in mind, and must communicate in detail about the research choices made. Why did the researcher focus on this particular purpose? Why did the researcher choose this particular measurement, and how is it defined? And last, which profiles have been included in the database? In this context, an elucidation of the legal regulations and the broader ethical discussion of the purpose and content of a DNA database seems a prerequisite.

Future research might progress the work developed here, as the study of the triangular relationship also relates to the efficiency of the DNA database: *"In an environment of limited resources, knowing which technologies provide the biggest benefit for solving crimes provides policy-makers with knowledge to support the expansion of certain practices or the reduction or elimination of others, as well as providing a base of information for criminal investigators weighing the opportunity costs of one choice over another"* (Wilson, McClure, & Weisburd, 2010, p. 468).

6 Conclusion

Although the selected studies are inconsistent in terms of study design, this article gives an up-to-date overview of the most relevant literature (in English and Dutch) on the effectiveness of DNA databases. Following the generally positive results reported in these studies, it can be hypothesized that forensic DNA databases do have an added value for police investigative work, the safety of society and criminological research, and thus are effective. However, some negative results and critical remarks cannot be ignored when drawing conclusions and making a comparison. Issues such as crime types (discussed in 4.1) and possible negative effects like crime displacement (discussed in 4.2) are important aspects to include in the discussion about the effectiveness of forensic DNA databases. These concerns need to be weighed against the gains obtained from their existence, use, and expansion. The current systematic review offers police and prosecutors insights into the added value that DNA databases can provide to link crime scenes and unknown offenders in specific crime cases. It offers policymakers the information they need when considering the use and possible expansion of their national DNA database. Last, it offers criminologists evidence for how DNA databases can provide an additional or alternative data source for their research on criminal behavior.

7 Appendices

7.1 Appendix 1: Databases surveyed

- Australian Institute of Criminology
- EconLit
- Hein Online
- Ingenta
- NCJRS
- ProQuest (selected databases: ASSIA, Criminal Justice Database, Criminology Collection, PAIS Index, Policy File Index, Social Services Abstracts, Sociological Abstracts and Worldwide Political Science Abstracts)
- Sage
- Springer
- SSRN
- Taylor & Francis
- Web of Science (selected categories: Criminology & Penology and Law)
- Wiley Online

7.2 Appendix 2: Data extraction sheet

N°	Article ID
R1	Study ID
R2	Date of analysis
R3	Title
R4	Author
R5	Funder
R6	Publication type
R7	Publication date
Q1	Hypothesis of the study
Q2	Objective(s) of the study
Q3	Research question(s)
Q4	Period examined
Q5	Country
Q6	Geography (single site; multiple site)
Q7	Spatial units
Q8	Methodology and design
Q9	Method and data sources
Q10	Data analysis
Q11	Effectiveness measured
Q12	Sample size
Q13	Participants (treatment and control groups)
Q14	Follow-up period
Q15	Crime types examined
Q16	Main results
Q17	Conclusions
Q18	Study limitations
Q19	Recommendations
Q20	Reviewers' comments

7.3 Appendix 3: Thematic questionnaire

N°	Article ID
R1	Study ID
R8	What did the study do?
QP1	What purpose is intended?
QP2	What is the definition of 'purpose' according to the study?
QP3	To which category does this purpose belong? ((i) detection and clearance; (ii) deterrence; (iii) criminological knowledge (iii))
QE1	How is effectiveness measured?
QE2	What is the definition of 'effectiveness' according to the study?
QE3	What is the measurement used to evaluate the effectiveness? (for purpose (i): identification rate, arrest rate, charge or prosecution rate, or conviction rate; for purpose (ii): recidivism rate or crime rate)
QC1	How is the DNA database used in this study? (independent variable, data source)
QC2	Which DNA profiles are minimally included in the DNA database? (individual's characteristics)
QC3	Which crime types are included in the DNA database?
QC4	To which category of profiles does this study apply? (reference profiles, forensic profiles, or both)
QR1	Is the DNA database effective according to the study?
QR2	If yes, based on which results?
QR3	If no, based on which results?
QR4	Does the author acknowledge the relationship between the purpose, content, and effectiveness of the DNA database?
QR5	If yes, how?
QR6	Is expansion of the DNA database needed according to the author?

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