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Human factors in forensic science: The cognitive mechanisms that underlie forensic feature-comparison expertise

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ABSTRACT

After a decade of critique from leading scientific bodies, forensic science research is at a crossroads. Whilst emerging research has shown that some forensic feature-comparison disciplines are not foundationally valid, others are moving towards establishing reliability and validity. Forensic examiners in fingerprint, face and handwriting comparison disciplines have skills and knowledge that distinguish them from novices. Yet our understanding of the basis of this expertise is only beginning to emerge. In this paper, we review evidence on the psychological mechanisms contributing to forensic feature-comparison expertise, with a focus on one mechanism: *statistical learning,* or the ability to learn how often things occur in the environment. Research is beginning to emphasise the importance of statistical learning in forensic feature-comparison expertise. Ultimately, this research and broader cognitive science research has an important role to play in informing the development of training programs and selection tools for forensic feature-comparison examiners.

1. The crossroads in forensic science

Forensic science plays a crucial role in the criminal justice system. Yet it is currently at a crossroads after a decade of critique from leading scientific bodies [1,2]. These criticisms highlight the lack of research investigating *how* and *how well* forensic feature-comparison examiners perform visual comparison tasks (e.g. 'matching' tasks). Consequently, researchers have begun investigating the reliability and validity of forensic feature-comparison performance, but the emerging picture has been mixed.

A key overview of *how well* examiners perform in their work [2] found that bitemark analysis was not foundationally valid, and had yet to be established for footwear examination, hair analysis and complex-mixture DNA analysis. Only single-source DNA analysis and fingerprint examination met the criteria for foundational validity. Beyond this overview, research has also shown that facial [3–5] and firearms examiners [6] can make accurate and reliable visual comparison decisions, and that document examiners have proficient handwriting comparison performance [7–9]. Importantly, this research has revealed that examiners in select disciplines meet the psychological definition of *expertise* by having characteristics, skills and knowledge that distinguish them from novices and less experienced people [10–12]. Fingerprint [13–15] and facial examiners [3–5] are more accurate in visual comparison tasks within their domain of experience than novices, and document examiners' proficiency stems from avoiding the errors that novices tend to make [7]. It is important to note that this expertise does not preclude error – even in fingerprint examination errors can range from 8.8% to 35% depending on the difficulty of the task [13,14].

But what underpins this expertise – or *how* is proficient performance achieved? Forensic feature-comparison examiners are ultimately human decision-makers [16]. It is therefore important to understand the psychological processes that underlie accurate decision-making. This has been vital in understanding expertise in other fields [17–21], and could lead to the development of training programs or selection tools to reduce errors in forensic decision-making. In this paper, we review current evidence on the perceptual and cognitive mechanisms associated with feature-comparison expertise, and highlight one specific mechanism – *statistical learning* – as a promising explanatory construct with implications for improved recruitment and training.

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2. Psychological mechanisms of forensic feature-comparison expertise

There are several cognitive mechanisms that distinguish forensic feature-comparison examiners from novices in visual comparison tasks.

2.1. Analytical and non-analytical processing

The visual comparison performance of examiners and novices can be differentiated by the interplay between analytical and non-analytical processing. Psychologists have long theorised that humans process information in one of two ways: non-analytically – sometimes called 'System 1' processing; and analytically – 'System 2' processing [22]. Non-analytical processing is fast, automatic and effortless. It is typically observed when individuals have limited time to make a decision. In contrast, analytical processing is slower, deliberate and effortful, and is observed when individuals have more time. The development of expertise is believed to be a process where a novice gradually transitions from analytical to non-analytical processing as their experience accumulates [23]. Yet, there is evidence that both types of processing may contribute to fingerprint and facial expertise [24].

Fingerprint examiners show evidence of both analytical and non-analytical processing. Consistent with non-analytical processing, they are more accurate than novices when given a limited time to determine if two fingerprints 'match' (just 400ms or 2s) [25,26]. Yet they also derive more benefit than novices when given more time to make decisions – consistent with analytical processing. Their accuracy increases by 19.5% when given 60 s to complete fingerprint comparisons (compared to 2 s) [25]. Novices' accuracy increases by only 6.8% when given the same additional time. Similarly, forensic facial examiners also show evidence of both analytic and non-analytic processing. Facial examiners are more accurate than novices when given 2 s to complete facial comparisons, but again derive greater benefit from more time [3]. Their accuracy increases by 12% when given 30 s, compared to novices' 7%.

Holistic processing is a type of non-analytical processing that differentiates the visual comparison performance of forensic examiners and novices. This is when humans process complex visual stimuli as one unified object, rather than a collection of random features – referred to as *featural processing* [27]. For example, most people process faces as a 'whole' face rather than as an assemblage of distinct facial features (i.e. eyes, nose, mouth) [27]. Holistic processing is typically measured by the degree to which an individual's ability to process stimuli as a 'whole' is disrupted.

Fingerprint examiners show evidence of processing fingerprints holistically [13]. Their accuracy is more negatively affected than novices when presented with 'partial' [13] or inverted and misaligned [28] fingerprints – although not when just inverted [25]. Fingerprint examiners also show electrophysiological evidence of holistic processing: the brain regions thought to be associated with holistic processing are activated differently in examiners and novices when viewing inverted fingerprints [13].

Facial examiners also show evidence of both holistic and featural processing. Consistent with holistic processing, facial examiners and novices both show worse accuracy for inverted than upright faces on 'match' trials [5]. Yet consistent with featural processing, facial examiners do not show a similar impairment on 'non-match' trials, whilst novices do [5]. Also consistent with featural processing, facial examiners' ratings of face features are more diagnostic of identity than novices', and they have better insight into some of the features that are most diagnostic (i.e. ears and scars) – although not others (i.e. cheek areas) [5]. Whilst fingerprint expertise appears to be characterised by holistic processing, its role in facial expertise appears to be more complex. This may be because all humans are considered to have a degree of 'expertise' in face recognition and already process faces holistically [29,30].

Forensic feature-comparison expertise is clearly a complex interplay between analytical and non-analytical processing. It is characterised by quick, intuitive and holistic processing like expertise in other domains [23] – such as chess [31] and musical notation [32]. However, slower, deliberate processing appears to enhance it – possibly by allowing to examiners to engage feature-by-feature comparison [5]. However, further research is needed to better clarify the relative roles of analytical and non-analytical processing in forensic feature-comparison expertise.

2.1.1. Future research directions

Existing forensic expertise literature typically interprets research with a dichotomous view of analytical and non-analytical processing [3,33]. Yet contemporary psychological research has begun to question this binary distinction. There may not be a clear-cut distinction between the two forms of processing. It is possible that analytical and non-analytical processing lie on a continuum [34,35], or even lie in a tri-dimensional space on continuums of speed (slow to fast), control (deliberate to automatic) and effort (effortful to effortless) [36]. It is therefore perhaps simplistic to suggest that forensic expertise operates via only one form of processing or the other.

For example, fingerprint and facial examiners outperform novices with limited viewing time [3,25]. From a dichotomous Type 1 vs. Type 2 view, this supports non-analytical processing. However, speed, control and effort may not necessarily operate in tandem in one system [36]. Forensic examiners may be more controlled under time pressure and utilise analytical processes quickly to improve efficiency – possibly by deliberately attending to more diagnostic information [5]. Indeed, fingerprint examiners show more consistent eye fixation patterns under time pressure than novices [37]. This could indicate that they may know better 'where to look.' Another alternative is that domain-specific visual comparison may require less effort under time pressure for examiners compared to novices. Ultimately, observed superior performance under time pressure may not exclude analytical processing. It is therefore important for future research to consider a multidimensional processing-space in order to better understand forensic feature-comparison expertise.

Bias is another important factor that should be considered in the role of analytical and non-analytical processing in feature-comparison expertise. Compared to novices, facial examiners are impaired on inverted face 'match' trials impairment (holistic processing), but no similar impairment on inverted 'non-match' trials (featural processing) [5]. However, erroneous 'match' decisions have more serious real-world implications in the justice system than erroneous 'non-match' decisions. Consequently, examiners could have bias towards making 'non-match' decisions – resulting in 'match' trial impairment, but not 'non-match' impairment [5]. Although there is no specific evidence of bias in the Towler et al. [5] study – examiners and novices did not significantly differ on the bias parameter ($C = 0.21$ and 0.03 respectively) – the explanation is generally plausible and worthy of further consideration [38]. Future forensic expertise research should continue to evaluate performance by differentiating between sensitivity (d') and bias (C) [38].

2.2. Memory retention

Memory processes also distinguish examiner and novice visual comparison performance. Evidence suggests some experts are better able to retain visual representations of relevant stimuli than novices [39]. For example, when briefly shown a chessboard mid-game, Master chess players are more accurate at reproducing those boards from memory than novices, particularly when the games are derived from 'legal' moves [39,40]. Similarly, fingerprint examiners are more resistant to memory decay for fingerprint stimuli than novices [13,25]. They are more accurate than novices when comparing fingerprints after a 200-ms [13] or 5-s delay [13,25]. This means that another mechanism that may underpin fingerprint expertise is being able to 'hold' fingerprints longer in memory than novices.

2.2.1. Future research directions

Whilst better retention of domain-specific stimuli characterises fingerprint expertise, no research has explored its role in facilitating visual comparison performance. Fingerprint 'matching' is typically considered to be a comparison task – not one of recognition. However, 'holding' one image longer in memory could possibly assist comparison between two simultaneously presented images. It is possible that this ability could reduce perceptual errors in comparing between images, or even increase an examiner's efficiency under time pressure [3,13,25]. Whilst research has demonstrated that this ability characterises forensic expertise, it has not clarified how it actually plays a role in their professional performance. Future research could explore whether memory retention better facilitates visual comparison performance.

2.3. Other cognitive mechanisms

There are several additional promising but less well-established cognitive mechanisms that differentiate examiner and novice performance. Fingerprint examiners: can locate more 'matching' fingerprint regions than novices [41]; are better able to generalise individual fingerprints from individual 'finger' categories to broader 'person' categories (i.e. identifying that two fingerprints from two different fingers belong to the same person) [42]; and are better able to identify outliers in fingerprint category arrays (e.g. a 'loop' in a 'whorl' array) [26]. Document examiners also show different visual search patterns than novices when identifying whether signatures are genuine, forged or disguised [43]. Whilst each of these cognitive mechanisms has only been identified in single studies, they are important and interesting avenues for future research.

3. Statistical learning and forensic feature-comparison expertise

Another cognitive mechanism that differentiates performance between forensic feature-comparison examiners and novices is statistical learning. Decades of psychological research has shown that humans can implicitly extract and encode statistical information from their environment [44–47]. For example, English language speakers are able to accurately rank which words occur more or less often in the English language [45,48]. People can learn everything from the conditional relationships between stimuli (e.g. A co-occurs with B) [49,50] to distributions in the environment (e.g. C occurs more often than D) [51,52] – from visual, auditory and even tactile stimuli [53,54]. Statistical learning can occur after only brief exposure to statistical information and without instruction to do so [49,51,55,56]. It is typically thought to be an innate and automatic ability that we all possess. Importantly, it also appears to play a role in forensic feature-comparison expertise [57].

Prominent mathematical theories suggest that rare statistical information is more important than common information in visual comparison tasks [58–60]. For example, a rare fingerprint feature (e.g. a 'lake) is more diagnostic of a 'match' between two fingerprints than a common fingerprint feature (e.g. a 'bifurcation') as it is shared between fewer people in the general population. If forensic examiners learn this statistical information over years of casework, they could use this learning to facilitate their visual comparison performance. There is some concern that this may mean examiners are relying on 'numbers from nowhere' [61,62] given the absence of quantitative statistical databases in many forensic disciplines [63]. However, it is also possible that naturally-acquired statistical learning over the course of many years' experience is accurate enough to facilitate superior feature-comparison performance. Below we review a series of studies that investigate this mechanism.

3.1. Forensic examiners' statistical learning

Emerging evidence has shown that forensic examiners in some disciplines have enhanced statistical learning for stimuli within their domain of expertise. For example, forensic document examiners have enhanced statistical learning for handwriting compared to novices. Martire, Growns & Navarro [64] asked novices and document examiners to estimate the frequency of handwriting features in the general United States population. They then calculated the accuracy of their estimates based on a 'ground-truth' database of the handwriting feature frequencies in the US [65]. Document examiners from the US had the best estimation accuracy, followed by document examiners from outside the US and then novices. US document examiners' estimates were also the most well-calibrated and precise as their mean estimates were closest to the true feature frequencies (calibration), and their individual estimates were most similar to each other (precision). Document examiners thus showed enhanced statistical learning compared to novices, that was both domain- (i.e. handwriting) and stimulus-specific (i.e. US handwriting).

Fingerprint examiners also appear to have enhanced statistical learning for fingerprints compared to novices. Mattijssen et al. [66]. asked fingerprint examiners and novices to estimate the frequency of fingerprint categories (e.g. 'whorls' or 'arches'), and then calculated their normalised estimation accuracy based on a 'ground-truth' database of fingerprint category frequencies in the Netherlands [67]. Fingerprint examiners had better normalised estimation accuracy than novices, and their ranking of the category frequencies were also better correlated with the 'ground-truth' rankings than novices'. Although examiners were not more accurate on all statistical learning measures in this study (e.g. unbounded 'natural' frequency estimates), it does provide some evidence that fingerprint examiners have better fingerprint statistical learning than novices. Overall, this emerging research suggests that statistical learning is another cognitive mechanism that contributes to forensic feature-comparison expertise.

3.2. Statistical learning in visual comparison tasks

Forensic examiners in some disciplines can use statistical information to facilitate performance in visual comparison tasks. Busey et al. [58] utilised the Attention via Information Maximisation (AIM) model to identify high and low diagnostic features and regions in a set of fingerprints. Fingerprint examiners' subsequent visual comparison accuracy was significantly more accurate for partial prints containing rare and diagnostic 'AIM' regions than prints containing less diagnostic 'AIM' regions. This suggests that access to computationally-identified statistical information improves visual comparison performance.

But can forensic examiners also rely on their *own* incidental statistical learning to facilitate visual comparison performance? Growns and Martire [57] familiarised forensic examiners from various disciplines (e.g. fingerprints, firearms and image comparison) with a set of artificial complex patterns containing rare and common features. They then completed an artificial comparison task where accurate performance could only be achieved via statistical learning. Forensic examiners learned what features were rare and common after familiarisation, and they performed significantly above chance in the artificial comparison task. This suggests that they were able to use their incidental statistical learning to facilitate visual comparison performance. This is quite striking given that the task was outside the domain of examiners' expertise.

The same study also identified a key factor in the relationship between statistical learning and visual comparison performance. Forensic examiners in some disciplines appear have an explicit understanding of some features that are diagnostic in their domain of expertise [5]. To investigate the role of explicit 'diagnosticity' knowledge, Growns and Martire [57] also trained a group of novices to understand the importance of diagnostic statistical information in visual comparisons. Forensic examiners and trained novices were equivalently able to learn which features were rare and common, but trained novices then outperformed forensic examiners in the artificial comparison task. Trained novices' statistical learning also significantly predicted their visual comparison performance – which was not the case for examiners. This result suggests that explicit 'diagnosticity' knowledge further enhances the ability to use statistical learning to facilitate visual comparison performance.

Decades of psychological research has shown that expertise is often domain-specific and does not generalise to other domains [40,68]. Importantly, examiners appear to have superior statistical learning within their domain of expertise, but not outside it. Examiners and novices can also use their statistical learning to facilitate visual comparison performance – even outside an examiner's area of expertise. Yet their explicit understanding of the *value* of diagnostic features in their domain of experience does not appear to generalise [5]. Training novices to understand the value of diagnostic features allowed them to more accurately make 'match' decisions using statistical information.

Nevertheless, it seems that statistical information can facilitate performance in forensic comparison tasks – whether computationally-identified or learned incidentally through experience. However, there is another important factor in this relationship. It is likely that an explicit understanding of the importance of diagnostic information is critical. Novices can develop this understanding via brief 'training,' but it is not known whether forensic examiners would also benefit from similar training.

3.3. Future research directions

It is possible that forensic examiners only have an explicit understanding of the value of diagnostic information within their area of expertise. The artificial pattern stimuli used by Growns & Martire [57] ensured the comparison task was outside examiners' domain of expertise. It is entirely plausible that examiners would outperform novices in statistical decision-making *within* their domain of expertise. It is even possible that this ability could be further enhanced by providing examiners with brief diagnosticity 'training.' It is important for future research to further examine the role of domain-specific and domain-general statistical learning in visual comparison performance, and the role of training in this relationship.

This research is also limited as it has only considered the role of statistical learning in isolation from other cognitive mechanisms. It is plausible that multiple cognitive mechanisms underpin forensic feature-comparison expertise that operate in tandem. Statistical learning could be utilised during holistic or featural processing. For example, even when perceiving a face as a 'whole,' individuals can still typically perceive a face that is rare or statistically 'unusual' (e.g. faces that are indicative of some diseases such as Bell's palsy). It is possible that forensic examiners utilise their superior domain-specific statistical learning implicitly and quickly in matching tasks – making them more efficient under time pressure than novices. Conversely, it is possible that statistical learning could be utilised during featural processing. Statistical learning could be engaged as a part of a slower, more deliberate feature-by-feature matching strategy. No research has investigated the relationship between statistical learning and holistic or featural processing.

Statistical learning could also operate via different memory processes. Some memory theories suggest that we store an 'average' of all exemplars in one category in our memories [69]. All novel category items encountered are compared with this 'average' and the difficulty of categorisation increases the further away novel exemplars are from the 'average.' Statistical learning could operate along with this process. For example, a fingerprint examiner could store an 'average' of all the fingerprints they had ever seen, and rare statistical information may be more salient as it is 'further away' from their stored average. Future research could consider the role that multiple cognitive processes – from statistical learning to holistic/featural or memory processes – play in forensic feature-comparison expertise.

4. Cognitive science research in forensic feature-comparison training and selection

Training is often believed to be critical in the development of expertise. However, emerging research has shown that some forensic feature-comparison training programs (i.e. facial examination training) are not effective in improving short-term visual comparison performance [70]. Similarly, research has shown that training can be ineffective in other disciplines [71,72]. Consequently, it is critical to identify empirically supported and effective forensic training programs [70,73]. Furthermore, it is important that these training programs consider the role of psychological factors in decision-making [73]. Cognitive science research has shown that there is a wide variety of psychological factors that are important in feature-comparison expertise. Yet it is not known the extent to which this research is incorporated into current training programs [73].

Although preliminary, one example of empirically-supported training is 'diagnosticity' training [57] – this increases the ability to use statistical learning to facilitate visual comparison performance. Whilst more research is needed, this is an example of how theoretical concepts can be used to develop applied interventions. It is possible that this kind of training could be included as a component in existing training programs to improve performance. It is even possible that research could inform the development of selection tools that identify examiners on the basis of cognitive abilities known to predict superior visual comparison performance – such as statistical learning [57]. For example, some law enforcement agencies have begun to select forensic facial staff on the basis of an ability known to predict superior facial comparison performance – superior face recognition (or 'super-recognisers') [4,74–76]. Cognitive science research is important in developing forensic training programs and could also assist in the recruitment of new examiners. However, it is important to emphasise the vital ongoing role that research should play in this. Skill-based examiner selection should only be considered using multiple empirically-based measures with robustly demonstrated reliability and validity.

5. Summary

Forensic examiners in fingerprint, facial and document examination are more proficient in visual comparison tasks than novices. Several psychological mechanisms appear to contribute to this expertise, including analytical and non-analytical processing, memory retention and statistical learning. Understanding the role these mechanisms play in visual comparison performance could be important for improving forensic training and selection. Future research should continue to investigate the human factors and cognitive mechanisms that play a role in forensic decision-making to improve feature comparison performance and criminal justice outcomes.

Declaration of competing interest

The authors have no conflicts of interest to report.

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