General discussion
Memory detection is a valuable tool for uncovering whether a criminal suspect possesses crucial knowledge about a crime, even if they deny it. Despite extensive research over the past few decades, the leakage problem, the countermeasures problem, the difficulty in selecting suitable items, and the limited applicability of the test have hindered the widespread adoption of this technique. The studies of the current dissertation explored the use of different modalities, measurements, and techniques to detect crime-related knowledge in an effort to address these challenges and improve the effectiveness of the method.

Summary of the main findings

In Chapter 2, the question of whether items are better presented pictorially or verbally in memory detection was addressed. To investigate this, participants were asked to encode verbal (e.g., the word “knife”) and pictorial (e.g., an image of a knife) crime-related items and hide their knowledge in a memory detection test consisting of a verbal and a pictorial part. The results showed that detection was more successful when items were encoded and tested in the same modality. Furthermore, recognition of verbally encoded items could not be detected in a pictorial test. These results highlight the importance of matching the modality of test items to the modality in which crime-related information was encoded to improve detection efficiency. Moreover, using a pictorial test could help prevent false accusations against suspects who only heard or read about the crime but did not enact it. This way, the leakage problem could be circumvented.

Chapter 3 delved into the new development of a memory detection technique based on eye movements, testing it with a mock crime design. Additionally, the study was the first to address whether the promising eye-tracking method could provide a solution for the leakage problem (e.g., Bradley et al., 2011). Participants were instructed to either commit a mock crime on campus (guilty participants), read an article about the crime (informed innocent
participants), or read an unrelated article (naïve innocent participants). Afterward, all participants were presented with an eye tracking memory detection task. Results indicated that it was possible to distinguish the guilty participants from the naïve innocents. Interestingly, it was also possible to distinguish the guilty participants from the informed innocent ones, bypassing the leakage problem. While the results are promising, the detection efficiency observed in this study was lower than in previous memory detection studies.

In Chapter 4, as one of the major promises of memory detection based on eye movements lies in the possibility of conducting tests remotely and without a laboratory setup, I took a first step in assessing the validity of webcam-based eye tracking. In the study, three robust eye tracking paradigms - the cascade effect, the novelty preference, and the visual world paradigm - were replicated online using the participant’s own webcam as an eye tracker. All three studies were replicated successfully, although the effect sizes were reduced by 20 to 27%. These findings indicate that online webcam-based eye tracking is feasible but also noisier than traditional laboratory-based eye tracking. However, as it has some important advantages as compared to traditional eye tracking, it could be preferable in certain cases. Based on these results, I suggest that eye tracking studies with relatively large effects that do not require extremely high eye tracking precision could be conducted online using participants’ webcam as eye tracker.

Chapter 5 introduced a novel approach for detecting crime knowledge by examining eye movements toward modified areas of a crime scene. After committing either a mock crime or an unrelated task, guilty and innocent participants viewed the crime scene (taken with a 360° camera) in virtual reality (VR) to which several salient modifications were made. The study found that guilty participants looked more and earlier at these modifications as compared to innocent participants and that it was possible to significantly distinguish them from each other based on their eye movements. This new method has various advantages as
compared to classic memory detection. Primary because it could be less susceptible to both the leakage and the countermeasures problems. In addition, as it is based on a presentation of the entire crime scene, it does not require control items. However, the detection efficiency in the current design does seem lower than classic memory detection methods.

Practical and theoretical implications

Implications in the field of memory detection

The current dissertation has some important implications for the field of memory detection. Examiners should always try to match the modality of the test items to the modality in which the crime information was encoded, which is mostly pictorial in nature. This way, the detection efficiency of the test could be maximized. In cases where a laboratory setup or direct contact with the examinee would not be possible, memory detection based on eye movements could be considered. Using this method with a webcam will enable large-scale memory detection programs where groups of people could be tested in a quick way (Kleinberg et al., 2019). VR-based memory detection could be used in cases where investigators have only limited information about a crime (e.g., if they do not know the murder weapon or how the perpetrator fled the scene). In these cases, a classic memory detection test would not be possible. However, using a modified 3D image of the crime scene would allow the identification of suspects with crime knowledge.

Overall, these studies have the potential to improve memory detection in several ways. First, they suggest new ways to overcome the leakage problem (Chapters 2, 3, and 5). By using a pictorial test when leakage happened verbally, by using eye movement-based memory detection (as it was possible to distinguish informed innocents from guilty participants), or by using VR-based memory detection with a modified crime scene (where leakage is less likely), innocent suspects could possibly be protected from being falsely accused. Second, these
methods could provide a solution to the countermeasures problem (Chapters 4 and 5). It has been shown that eye movements can happen outside one’s awareness, making them potentially more resistant to countermeasures (Lancry-Dayan et al., 2022; Ryan et al., 2000). Third, they could resolve the problem of the difficulty in selecting suitable control items (Chapter 5). The VR-based memory detection paradigm requires only a 360° picture of the crime scene, eliminating the need for control items. Last, these methods could be applicable to more settings than traditional memory detection (Chapters 2, 3, and 4). No lab, experienced examiner, or dedicated and expensive hardware is needed for these methods, which highly increases the test’s applicability. In sum, the four chapters contribute to the growing body of research on memory detection and demonstrate the value of exploring different methods and measures for detecting crime knowledge.

Implications for the broader scientific community

Besides the field of memory detection, the current findings also have some implications for the broader scientific community. Chapter 2 contributes to the growing research on the picture superiority effect. There are two competing theories explaining pictures’ mnemonic advantage over words. First, there are those attributing it to a perceptual processing advantage. Whereas pictures can be encoded through both the verbal and the nonverbal memory pathway, words can only be encoded through the verbal pathway (the dual-code theory; Paivio, 1971). Second, there are those attributing it to a conceptual processing advantage. Cognitive operations performed during encoding are reinstated during retrieval. Since a typical memory test requires the examinee to retrieve information visually, pictures are at advantage (the transfer-appropriate processing theory; Rugg et al., 2015). The results reported in Chapter 2 support both theories and suggest the two might not be mutually exclusive. As predicted by the dual code theory, items that were encoded pictorially were easier to detect than items that were encoded verbally. Furthermore, no conversion across
modalities was observed when items were encoded as words. As predicted by the transfer-appropriate processing theory, recognition effects were strongest when encoding and test modality were matched.

Chapters 3 and 5 contribute to the literature on the link between eye movements and memory. In these studies, guilty participants looked more at the crime-related items (Chapter 3) and the modifications (Chapter 5). This is in line with the orienting response theory according to which people look more at objects that are significant to them or differ from their expectations (Sokolov, 1990). This behavior is essential for adapting to a constantly changing environment, as it enables us to quickly make decisions and navigate through the world (Hannula et al., 2010). These responses are not only visible in eye-movements, but also in other physiological and behavioral responses (Lynn, 1966).

Chapter 4 has several important practical implications for the wider scientific community as it demonstrates the feasibility of eye tracking research to move beyond the confined lab and onto the web. This enables research to be conducted considerably faster, easier, and cheaper without the need for a lab, experimenter, or dedicated hardware. Moving online also opens up the possibility of recruiting a larger and more diverse participant pool, including even those who are hard to reach. The collection of data would no longer be limited by time or location as individuals could participate whenever they want, wherever they want.

Limitations and future directions

Lower detection efficiency

One of the major challenges of the methods presented in the current dissertation is that their detection efficiency seems generally lower than what is usually found with classical memory detection methods. For example, in Chapter 3, eye movement-based memory detection resulted in a detection efficiency of 0.71. In Chapter 5, VR-based memory detection
resulted in a detection efficiency of 0.75. In contrast, a recent review by Lancry-Dayan et al. (2022) showed that physiological measures (skin conductance, heart rate, and respiration) result on average in a detection efficiency of 0.81, neural activity result in a detection efficiency of 0.91, and eye movements (in a parallel design) in a detection efficiency of 0.86. As such, while the new methods presented in the current dissertation offer important advantages as compared to traditional memory detection, there is still much room for improvement in terms of their detection efficiency.

One of the reasons for the lower detection efficiencies found in the current dissertation could be that only newly learned items were used, while the averaged detection efficiency scores of 0.86 included studies in which highly familiar items (e.g., the face of a best friend) were used. Research has shown that newly learned items typically result in lower detection efficiency scores than highly familiar items (Lancry-Dayan et al., 2021; Millen et al., 2017, 2020). Furthermore, in the current studies, participants learned the crime-related items during a mock crime, whereas many other studies included in the average detection efficiency score used a memory game. While memory games guarantee optimal memory, a mock crime does not necessarily result in participants seeing and remembering all relevant information. This poorer memory for crime-related items might have decreased the efficiency scores even further. To compare the different methods more accurately, future studies should conduct a memory detection test while measuring eye movements, physiological measures, and neural measures simultaneously.

**Webcam-based memory detection**

In this dissertation, I did not use webcam-based eye tracking as a measure for memory detection. Although it would have seemed a logical next step, our studies suggested that it might be too early to combine the two methods. Chapter 3 showed that while memory detection based on eye movements was possible, effect sizes were relatively small. Chapter 4
revealed that large effects and few regions of interest are necessary for valid results. Therefore, I concluded that it might be premature to conduct a memory detection test with a participant's webcam at this point. Nonetheless, I predict that advancements in webcams, cameras, and machine learning will make this a possibility in the near future. For example, new methods that incorporate deep neural networks have been developed for measuring eye position in smartphones (Valliappan et al., 2020).

Moreover, eye tracking is not the only method that is constantly improving. Portable devices can now measure skin conductance, heart rate, breathing rate, and even neural signals (for example by portable EEG or functional near-infrared spectroscopy; Ferrari & Quaresima, 2012; Krigolson et al., 2017). This could make these measures more widely applicable as well. Future research could explore the detection efficiency of these portable devices and how the different measures could be combined to increase overall accuracy and reliability.

Memory detection to search for information

Chapter 5 found that someone with crime knowledge can be detected by taking them back to the crime scene in VR. This approach could possibly also be applied to the searching memory detection test (Breska et al., 2014; Osugi, 2011). For example, if investigators have already identified the perpetrator, they can use this test to detect the critical items (e.g., the location of a bomb). Clearly, this requires additional research.

Conclusion

In four chapters, the current dissertation explored several new methods to improve memory detection. I found that it is possible to detect crime knowledge by using eye movements, either by examining them with respect to crime items presented along with control items or pertaining to modified areas of a crime scene. In the future, these eye movement-based memory detection methods could possibly be used with a webcam, but for
now, webcam-based eye tracking should remain limited to studies with large effect sizes and few areas of interest. In all memory detection tests, the modality of test items should be matched to the modality in which crime information was encoded to improve detection efficiency. The methods explored have the potential to improve memory detection in several ways, working towards a solution to the leakage problem, the countermeasures problem, the difficulty of identifying proper items, and the limited test applicability. The findings have important implications for memory detection in criminal investigations and highlight the need for continued research to optimize its use. The findings also convey novel insights to the basic science literature related to the connection between memory and eye movements, as well as the picture superiority effect. In conclusion, while the idea of mind reading depicted in popular media remains futuristic, research proves that significant steps have already been made in the right direction. As technology continues to advance, we can only look forward to more innovative methods to detect crime knowledge, making it easier than ever to read the criminal mind.
CHAPTER 6

References


Valliappan, N., Dai, N., Steinberg, E., He, J., Rogers, K., Ramachandran, V., Xu, P.,
English summary
Reading the criminal mind

Exploring novel methods of memory detection

To examine whether a criminal suspect has implicating crime knowledge, recognition of crime-related details can be detected using memory detection methods. Despite decades of research demonstrating its effectiveness, only the Japanese National Police has been using it extensively in criminal investigations. Wider adoption of this method faces several challenges, including the leakage problem, the countermeasures problem, the difficulty in selecting suitable testitems, and the limited applicability of the test. In the current dissertation, various modalities, measurements, and techniques are explored in an effort to address these challenges and improve the effectiveness of the method.

The current dissertation comprises four lines of research. First, I examined which modality (verbal versus pictorial) is optimal for memory detection and whether encoding and testing modalities interact. The results highlight the importance of matching the modality of the test items to the modality in which crime-related information was encoded to improve detection efficiency. Second, I explored the promising new development of memory detection based on eye movements, including its potential of solving the leakage problem. Results indicated that it was possible to distinguish the guilty participants from the naïve innocent participants as well as the informed innocent ones based on their eye movements. Third, as a first step in assessing the potential of webcam-based eye tracking for memory detection, I examined whether a simple webcam could be used as an eye tracker. To this end, I replicated three robust eye tracking studies online using the participant's webcam as an eye tracker. The results suggest that webcam-based eye tracking is feasible, although it is best suited for studies with relatively large effects that do not require very high eye tracking precision. Fourth, I introduced a new approach for detecting crime knowledge by examining whether suspects' familiarity with a crime scene could be detected by bringing them back to a
modified version of it in virtual reality. We tested whether gaze behavior toward the modified parts of the crime scene could reveal its recognition. The study showed that guilty participants looked more and earlier at the modifications than innocent participants, making it possible to significantly distinguish the two groups from each other.

The findings have important practical implications for memory detection as well as theoretical implications for the memory literature. A wider application of memory detection can bring us one step closer to reading the criminal mind.
Dutch summary
Het lezen van de criminele geest

Onderzoek naar nieuwe methoden voor geheugendetectie

Om na te gaan of een verdachte van een misdrijf over daderkennis beschikt, kan herkenning van misdaad gerelateerde informatie worden getest met behulp van geheugendetectiemethoden. Hoewel onderzoek de doeltreffendheid van de methode reeds tientallen jaren heeft aangetoond, gebruikt tot op vandaag alleen de Japanse nationale politie deze methode op grote schaal in strafrechtelijke onderzoeken. Bredere toepassing van de methode kent verschillende uitdagingen, waaronder het lekprobleem, het probleem van tegenmaatregelen, de moeilijkheid om geschikte testitems te selecteren en de beperkte toepasbaarheid van de test. In het huidige proefschrift worden verschillende modaliteiten, metingen en technieken onderzocht in een poging deze uitdagingen aan te pakken en de effectiviteit van de test te verbeteren.

Het huidige proefschrift bestaat uit vier onderzoekslijnen. Ten eerste heb ik onderzocht welke modaliteit (verbaal versus pictoriaal) optimaal is voor geheugendetectie en of codering- en testmodaliteiten op elkaar inwerken. De resultaten benadrukken het belang van het afstemmen van de modaliteit van de testitems op de modaliteit waarin misdaad gerelateerde informatie werd gecodeerd om de efficiëntie van de detectie te verbeteren. Ten tweede onderzocht ik de veelbelovende nieuwe ontwikkeling van geheugendetectie op basis van oogbewegingen, inclusief de mogelijkheid om het lekprobleem op te lossen. De resultaten gaven aan dat het mogelijk was om de schuldige deelnemers te onderscheiden van de naïeve én de geïnformeerde onschuldige deelnemers op basis van hun oogbewegingen. Ten derde, als een eerste stap in het beoordelen van het potentieel van webcam-gebaseerde eye tracking voor geheugen detectie, onderzocht ik of een eenvoudige webcam gebruikt kan worden als eye tracker. Daartoe replicaerde ik drie robuuste eye tracking studies online met de webcam van de proefpersoon als eye tracker. De resultaten suggereren dat webcam-gebaseerde eye
tracking mogelijk is, hoewel het voorlopig het meest geschikt is voor studies met relatief grote effecten die geen zeer hoge precisie vereisen. Ten vierde introduceerde ik een nieuwe aanpak voor het detecteren van daderkennis door te onderzoeken of de herkenning van een plaats delict kon worden gedetecteerd door verdachten naar een aangepaste versie ervan te brengen in virtual reality. We testten of het kijkgedrag naar de aangepaste delen van de plaats delict de herkenning ervan kon onthullen. Uit het onderzoek bleek dat schuldige deelnemers meer en eerder naar de aanpassingen keken dan onschuldige deelnemers, waardoor de twee groepen significant van elkaar konden worden onderscheiden.

De bevindingen hebben belangrijke praktische implicaties voor geheugendetectie alsook theoretische implicaties voor de geheugenliteratuur. Een bredere toepassing van geheugendetectie kan ons een stap dichter brengen bij het lezen van de criminele geest.
Hebrew summary
קריאת המחשבה הפילינית

חקר שיטות חדשות לזיהוי זיכרון
כדי לבחון האם חשוד בפלילים
קשור לפשע מסוים, ניתן לבחון זיהוי של פרטים הקשורים לפשע באמצעות שיטות
ליזיהון מידע מוכמן. לфорמט בשנים של מחקרים שונים, איים וＸתרしま וחינה לשון והמחמוד עם מספרו הפריר, לברוח
בגימול צעדים, עניין מעין אחר, קדר חיבור פריטיםماتראים והיוות הזיהום המגובד של המבוק.
בעובדות המגדלות, המשכיות אופטימיות, מצודות השכונות שуют שבמאמץ להפוך את המתחים אל השלום את
היעילות השוטה.

עובדות המגדלות ורבות במאוביגות קוית מחקר. ראויה, בדקתי את המגדלות אופטימיות של זיהוי זיכרון
והאמ כמה קידוד המזרחי mụnיפוץ על אופנים ההדיקה האופטימיות. התמצאות תמורת ושתיות התמונות על התמצאות
האמונה של פריטי הדיקה לאפים שבר줍 דמצוד זיהויו ועלしな ציון. בדקתי את המתחים והמחמודים
תורשה של זיהוי זיכרון המבוסס על תנועות עיניות. בנוויה, בדקו את ההשד והמשתמשים הממוצעים בקנוני
המצאות הצבעי על כל שיתוף הלחצתי בין משスタートים אופטימיות בהמפעים הממוצעים על פעולות של
سكن תועשות מינימיות שלמה. שילוחית, בצונא ראוושה מהציורית הפוטנציאלי של מעבד תועשות ייצוגים של מצוק מובוס מצלמת אופטומטר
ליזיוו זיכרון, בדקתי את המגדלות של מ赕ים אופטימיות של תועשות ציון מзависимות בצומת הפרעה של
שלולאות המגדלות קוליסים עם אפקט⛲ים בבריר של תועשות ייצוגים אופטימיות בתזירותנית עמשלת המתחים. המתחמות
מצבוע על כל שמעתק תועשות מובוס מヅלאת אופטימיות אופטימיות, אם כי היא מאמצת יוהר למתוחים עם אפקט㨳ים
לוזיים זיזים שאיננו דרשים דיק במדידת זיוד הפקמה המבוק. ריבית, הצגתי גישה לאוטור מדיד
מקומון. בדקתי את גいった ליזיוו ألיזיוו לאטור שה)index של חוסף אעם הזיווי על הזיווי ליזיוו המשוער
שינים בציציוואת מבודד. בדקתי את החיתות המבוסס על חזרה בידק בבריר של ייצוגים אופטימיות בבריר התמרות
מקומון על הזיווי. המחקר הרהזא עם משスタートים אופטימיות העבורה ויתור מזיקה על השינויים אופטים
משスタートים המבוק, במ האיימיס הלוחבון במדידות שבית הקבוצה.
לממצאות זו קמצחה מועשיש תשובה על זיודו היצוי וההעשות התאודיות על מחקר זכרון וקובב.
הขาלו מקוברים אוחנה עתא לאליזיוו זיודו מודריך של מיזידע פילילי מקומון.
Author contributions
Chapter 2: Modality effects in memory detection


Ine Van der Cruyssen, Gershon Ben-Shakhar, Yoni Pertzov, and Bruno Verschuere developed the study concept. Ine Van der Cruyssen and Franziska Regnath set up the experiments, collected the data, and performed the statistical analyses. Gershon Ben-Shakhar, Yoni Pertzov, and Bruno Verschuere provided critical feedback. All authors contributed to and approved the final version of the manuscript for submission.

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Chapter 3: Memory detection based on eye movements


All authors contributed to developing the study concept and design. Ine Van der Cruyssen programmed the experiment, performed the statistical analyses, and drafted the manuscript. All co-authors provided critical feedback on the manuscript and approved the final version of the manuscript for submission.

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Chapter 4: The validation of webcam-based eye tracking

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Ine Van der Cruyssen, Gershon Ben-Shakhar, Yoni Pertzov, and Bruno Verschuere developed the study concept. Nitzan Guy programmed the experiments. Ine Van der Cruyssen, Quinn Cabooter, and Lukas Gunschera created the materials, collected the data, and performed the statistical analyses. Gershon Ben-Shakhar, Yoni Pertzov, and Bruno Verschuere provided critical feedback. All authors contributed to and approved the final version of the manuscript for submission.

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Chapter 5: Memory detection in virtual reality: The effect of scene modifications


All authors contributed to developing the study concept and design. Ine Van der Cruyssen set up the experiment and conducted the statistical analyses. Gershon Ben-Shakhar, Bruno Verschuere, and Yoni Pertzov provided critical feedback. All authors contributed to and approved the final version of the manuscript.

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