Gaze and Memory: An Investigation into the Role of Eye Movements in Maintaining Verbal and Spatial Information

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A thesis submitted to Cardiff University
for the degree of Doctor of Philosophy

April 2024

Summary

This thesis aims to investigate the role of gaze shifts during encoding and maintenance of verbal and spatial information and explore potential moderating factors. *Chapter 2* examined the influence of the type of information to be recalled and predictability of recall order on oculomotor behaviour. Results replicated previous findings of lower probability of looking at presented items when encoding spatial compared to verbal information, and more looks towards locations of previously presented items when maintaining spatial information, which was further boosted when the recall order was not predictable. To examine the role of long-term memory, *Chapter 3* explored eye movements when encoding and retaining verbal information that has a familiar spatial layout compared with the same verbal information presented in a novel layout. Results showed gaze patterns differ, suggesting recruitment of different spatial rehearsal strategies. *Chapter 4* examined eye movements in a novel task separating presentation and recall locations to distinguish between gaze indicative of rehearsal and output preparation. Results showed a gaze bias towards memorised locations and towards action-relevant locations when recalling spatial information compared to verbal information. Limited evidence for these observed gaze patterns influencing memory performance was found, with looking back to locations that previously contained memory items being indicative of rehearsal attempts. Despite multiple biases influencing eye movements, oculomotor behaviour revealed looking towards previously presented items, but the lack of a clear link between gaze patterns and recall suggests that gaze can provide limited support for spatial rehearsal. These findings can help refine current working memory theories by highlighting the limited role of eye movements in spatial memory maintenance.

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Acknowledgements

First and foremost, I extend my deepest gratitude to my supervisor, Doctor Candice Morey. Your unwavering encouragement and belief in my capabilities have been a guiding light throughout this challenging yet rewarding journey. Your mentorship has not only shaped my academic path but has also given me the confidence to pursue my research with vigour and dedication.

My heartfelt thanks go out to all those who have supported me academically. To my mentors and colleagues, Doctor Hana D'Souza and the Cardiff Babylab, Professor Merideth Gattis, Doctor Dominic Guitard, Doctor Georgina Powell, Doctor Travis Proulx, and Doctor Christoph Teufel, your insights and guidance have been instrumental in my growth as a researcher and an educator. Thanks to Professor Petroc Sumner and Professor Katherine Shelton for providing me with the opportunity to teach alongside my PhD. I would also like to thank Professor Benjamin Tatler and Professor Louise Phillips, your guidance and belief in my potential have been pivotal in shaping the path I find myself on today.

To my mother and the rest of my family, whose unconditional love and support have served as my foundation, and to my partner, Matthew Argyle, alongside the entire Argyle family, whose patience, understanding, and unparalleled support have been nothing short of amazing. Thank you for being my pillars, cheering me on, and making sacrifices that have paved the way to this milestone. I am equally grateful to all of my friends, whose encouragement, laughter, and companionship have transformed this journey into a less daunting and far more enjoyable adventure.

Finally, I dedicate this PhD thesis to my beloved grandmother and aunt, whose passing during my PhD journey left a profound void. Your love, wisdom, and values continue to shape who I am. Although you are not here to share this moment, this achievement is a tribute to you both. I hope I have made you proud.

Disclaimer

The data presented in *Chapter 3* were collected jointly by Baz Van De Vegte and myself, and the data in *Chapter 4* was collected jointly by myself, Hamdi Abdulahi and Emily Gwatkin. Experiment 1 in *Chapter 3* was implemented by Lotje van der Linden and all other experiments were implemented by me. A version of *Chapter 3* has been submitted for publication to Quarterly Journal of Experimental Psychology with co-authors: Richard J. Allen, Jelena Havelka, Stephen Darling, Baz van de Vegte, and Candice C. Morey.

1 General Introduction

1.1 Working memory, attention, and eye movements

Working memory is a limited resource which allows us to hold a handful of items in our mind simultaneously (Cowan, 2001, 2010) and enables the storage and manipulation of information, requiring active rehearsal to prevent loss of information (Baddeley et al., 2021; Barrouillet & Camos, 2021; Cowan et al., 2021). It is widely accepted among leading theoretical frameworks that there exists a dynamic interplay among visual, verbal, and spatial information, which is further enhanced by the influence of prior knowledge from long-term memory (e.g. Gonthier, 2021). The involvement of these elements in any specific scenario is likely influenced by the context of the task at hand. Exploring how these different components contribute to task execution and attention is crucial for a deeper comprehension of working memory and identifying ways to improve it. The successful execution of many everyday tasks relies on the maintenance and retrieval of relevant information. To safely navigate the world, we need to continuously keep in mind the locations of people and objects even when they are no longer in our field of vision. Selecting relevant information derived from the sensory stream in our external environment and in the internal space of memory is vital for interacting with a dynamic environment, with working memory allowing us to look both to the past and to the future.

While some working memory models posit that visual and verbal information are rehearsed in specialised short-term memory buffers or rehearsal mechanisms (Baddeley et al., 2021; Barrouillet & Camos, 2021; Logie, 2011), other models propose a domain-general maintenance system that retains stimuli from different sensory domains (e.g. Cowan et al., 2021), with recent research providing evidence against the need of a specialised visual-spatial short-term memory (for a review, see Morey, 2018). This thesis attempts to further investigate potential asymmetries by exploring eye movement patterns. However, the links between working memory, attention, and eye movements are first reviewed.

Several paradigms have contributed to our understanding of attention. The Posner paradigm (Posner, 1980) is a foundational experimental technique used to study attention, particularly the ability to shift attention spatially without moving the eyes. This paradigm involves participants responding to a stimulus that appears at a predictable or unpredictable location on a screen. Typically, a cue (consisting of a centrally presented arrow, word or digit) indicates where the next stimulus will appear, which can either accurately or inaccurately predict the actual location of the stimulus. The participants' task is to detect the stimulus as quickly as possible, often by pressing a button. The time it takes for participants to respond (reaction time) is measured, with shorter reaction times indicating more efficient attentional shifts. The Posner paradigm has been instrumental in distinguishing between different types of attention, such as overt versus covert attention (where overt attention involves moving the eyes to the stimulus, and covert attention does not) and has significantly contributed to our understanding of how attention is oriented and managed in the visual field. This type of cueing is seen as top-down as participants are instructed to use this information to improve their performance. A similar task but including cues with no predictive value for the upcoming location of the target, presented either at the location of the target or not, was also found to induce spatial cueing effects, with faster and more accurate responses when the cue and target appear at the same location. This finding has been considered as evidence that this type of cueing is bottom-up (e.g. Yantis & Jonides, 1990)

Attention can be oriented towards not only sensory data but also towards content held in working memory (WM). The concept of an inward-directed focus of attention is supported by the retro-cue effect, which demonstrates enhanced performance in visual WM tasks when attention is pre-emptively directed to the relevant contents of WM. The retro-cue paradigm has been instrumental in providing a practical framework for studying the capabilities and boundaries of attentional focus within WM.

Retro cues, as discussed by Souza and Oberauer (2016), function similarly to the cues in the Posner paradigm (Posner, 1980), guiding attention to where a relevant stimulus is expected to appear. However, a key difference is that, unlike the cues in the Posner paradigm that are presented before a stimulus, retro cues are introduced after stimuli have been encoded into memory. Their role is to direct attention to specific items within working memory. This process of attentional direction is believed to improve the retention and retrieval of the highlighted item, leading to better recall outcomes than in situations where attention is spread evenly among all items (Griffin & Nobre, 2003; Lepsien et al., 2005; Sligte et al., 2008). Findings from these paradigms point to the multiple ways in which attention can be biased towards locations of presented, memorised, and action-relevant items. While research has found a strong link between visual working memory, attention, and eye movements (for reviews see Theeuwes et al., 2009; van Ede, 2020), the link with verbal working memory is weaker. The next section briefly reviews key findings of these different links.

Before an eye movement is executed, attention is already shifted towards the saccadic goal (Deubel & Schneider, 1996). Strong links have been found between attention and large saccades (Findlay & Gilchrist, 2003; Gowen et al., 2007; Yarbus, 1967). Despite individual differences in preferences of saccadic control, with some participants choosing more, and others less saccadic activity (Laeng & Teodorescu, 2002; Ridgeway, 2006), detecting eye movements can provide further insight into the relationship between eye movements and selecting an item from working memory. The aim of this thesis is to examine if and how we use our eyes to encode and maintain information, and if any patterns are indicative of rehearsal boosting memory performance.

Eye movements and visuospatial attention are suggested to be highly related (Chelazzi et al., 1995; Deubel & Schneider, 1996; Smith & Schenk, 2012), with oculomotor behaviour suggested to have a specific role for maintenance in visuospatial working memory (Baddeley, 1986; Belopolsky & Theeuwes, 2009a, 2009b; Morey et al., 2018; Pearson et al., 2014; Postle et al., 2006; Schut et al., 2017; Theeuwes et al., 2005, 2006; Tremblay et al., 2006). Further research has investigated both saccadic interference and rehearsal benefits in visuospatial working memory. While covert attentional shifts have been found to interfere with spatial working memory, eye movements have been shown to interfere to a greater extent (Lawrence et al., 2004; Pearson & Sahraie, 2003), supporting the view that there is a tight link between eye movements and spatial memory maintenance. Moreover, eye movements to nonmemorized locations during the retention interval interferes with spatial memory (Hale et al., 1996; Postle et al., 2006).

Despite the strong link, there are mixed findings regarding the degree of use and direction of eye movements during retention of visuospatial information. For example, low oculomotor activity was observed during the retention period of a spatial memory task (e.g. Pearson and Sahraie, 2003, Experiment 5). They presented participants with an array of blocks and asked them to recall a specific sequence of blocks that was highlighted one by one. During a 5-second retention period after all the blocks were highlighted, a blank screen without a fixation cross was presented. While an EOG (electrooculography) analysis of the retention period revealed that during the practice trials participants adopted a strategy in which they used eye movements to attempt to recall the locations, rapidly thereafter a strategy of keeping the eyes still was adopted even without the presence of a fixation cross to keep their eyes focused. The participants also reported that overt eye movements were making it harder for them to recall the locations accurately. These findings provide little evidence of the use of eye movements as rehearsal mechanism or spatial working memory.

Furthermore, when natural saccade behaviour is disrupted, an interesting pattern has been suggested to emerge: saccade trajectories deviate away from memorized locations (Theeuwes et al., 2005, 2006) and saccadic latencies into the hemifield where a location had to be remembered increase (Belopolsky & Theeuwes, 2009b). In contrast to these findings, Tremblay et al., (2006) argue that the rehearsal of visuo-spatial information is achieved by eye movements, with some research suggesting that participants regularly look at the empty location where a memory item was previously presented, a phenomenon termed looking-at-nothing (Ferreira et al., 2008; Richardson & Spivey, 2000; Scholz et al., 2018). Eye movement patterns during imagery have also been found to be correlated with eye movements during encoding of the image, with the similarity between those patterns suggested to predict performance (Laeng & Teodorescu, 2002; but for opposing view see Foulsham & Kingstone, 2013; Johansson et al., 2012). High similarity of eye movements in the delay period with those during encoding has also been found by Olsen et al. (2014) and this pattern has been found particularly for increased task difficulty (Wynn et al., 2018).

Researchers often limit task designs to memory for one item (Awh et al., 1998; Belopolsky & Theeuwes, 2009b, 2009a; Boon et al., 2016; Henriques et al., 1998; Hollingworth & Luck, 2009; Sprague & Serences, 2013), as analysing the period during the retrieval of several items can include a longer sequence of saccades that might become idiosyncratic and less traceable between observers as they can engage in several different strategies during the time course. Despite the discussed above mixed findings, more recent research points to potential methodological and conceptual improvements that could provide a better understanding of the link between eye movements and working memory. Specifically, in a series of experiments van Ede et al. (2019) asked participants to remember multiple coloured and oriented bars in order to reproduce the orientation (Experiments 1-3) or colour (Experiment 4) of one of them after a short memory delay with a fixation cross on the screen.

The bar to be recalled was indicated by a change of colour (Experiment 1-3) or shape (Experiment 4) of the fixation cross. Participants were then prompted to respond by the appearance of a response dial. Despite the spatial locations of the memory items not being necessary for the task, van Ede et al., (2019) revealed that selecting an item from memory produced a higher proportion of gaze shifts towards compared to away from the memorized location of the probed item across all experiments. Importantly, the magnitude of these gaze shifts was small, suggesting a looking-towards-nothing rather than looking-at-nothing phenomenon. This finding supports a grounding role (Awh & Jonides, 2001; Dell'Acqua et al., 2010; Kuo et al., 2009; Theeuwes et al., 2011) of spatial location in prioritising and organising visual working memory and suggests that eye movements are utilised for visual working memory even when the location of the memory item is never tested.

Considering the findings of both van Ede et al., (2019) and those from Pearson and Sahraie (2003; Experiment 5), the degree to which participants need to engage with the items emerges as an important factor for oculomotor behaviour when selecting information from memory. Indeed, repetitive testing of the same pieces of information has been associated with diminishing looking-at-nothing behaviour (Scholz et al., 2011; Wantz et al., 2016), while when participants actively engage with information to make decisions or inferences, looking-at-nothing has been found to be stable (Jahn & Braatz, 2014; Scholz et al., 2015, 2017). Similarly, the higher oculomotor activity found in van Ede et al., (2019) compared to Pearson and Sahraie (2003; Experiment 5) could be due to the task involving an active selection of an item based on a retro cue instead of the more passive recalling a sequence of items. To summarize, while the strong link between eye movements and maintenance of visuospatial working memory has been established, there are mixed findings regarding the degree of use and the direction of oculomotor behaviour during retention of visuospatial information.

Research has delineated two primary maintenance mechanisms of verbal working memory: an articulatory process, which seems to utilize similar functions as language production and is specific to verbal information, and a domain-general attentional process that supports the retention of both visuospatial and verbal information (Camos et al., 2009; Camos & Barrouillet, 2014; Camos, 2015, 2017; Camos et al., 2011, 2013; Hudjetz & Oberauer, 2007; Mora & Camos, 2015; Mora & Camos, 2013; Rose et al., 2015; Vergauwe et al., 2014). Although these mechanisms can operate together in preserving verbal representations, they are believed to function independently, with each susceptible to different types of interference: the articulatory process can be disrupted by simultaneous speech, given its reliance on linguistic functions (Baddeley, 1986; Baddeley et al., 1975), while the attentional mechanism can be hindered by tasks that divert attention (Barrouillet & Camos, 2015, for a review). These two independent maintenance mechanisms might explain why the connection between eye movements and the maintenance of verbal information is comparatively tenuous. Shifts in attention are believed to be less disruptive to verbal working memory than to spatial working memory (Lawrence et al., 2004). Similarly, directing eye movements to relevant spatial positions has not been shown to significantly enhance the retrieval of verbal memory beyond the effect of covertly shifting attention (Scholz et al., 2018). Possibly because of these two distinct maintenance mechanisms and their presumed autonomy, the maintenance of verbal information appears to be less connected to attention and eye movements. This is supported by suggestions that shifts in attention do not disrupt verbal working memory as much as they do spatial working memory (Lawrence et al., 2004). Additionally, moving the eyes to spatial locations related to the memory does not enhance verbal memory retrieval more than merely shifting attention without eye movement (Scholz et al., 2018). Several studies have investigated eye movements during encoding and during retrieval of verbal and visuospatial information. Czoschke et al. (2019) investigated eye movement behaviour during the encoding of verbal or spatial information. In their first experiment, they presented participants with five bigrams in a sequential manner on different locations on a ring, each presented for 1 second with no delay between items. Participants were then instructed to report either the bigrams, their positions, or both the position and the bigrams in order of presentation. They found that saccades to to-be-remembered items were scarce during encoding of spatial information in comparison with verbal information. Despite this pattern, they did not find a link between item fixation and memory performance. In contrast to this pattern of higher fixation probabilities on memory items during encoding of verbal compared to spatial information, their results revealed lower regression probability to locations that previously contained to-be-remembered items at the end of the encoding period in the spatial and combined conditions than in the verbal condition. Moreover, this looking-at-nothing behaviour was associated with increased spatial memory performance. These fixations to empty locations which previously contained memory items were targeted at the first presented item (a similar pattern was observed by Lange & Engbert, 2013). To summarise, these findings suggest that more precise eye movements to to-be-remembered items are needed for encoding verbal information compared to those needed to encode spatial information, with the opposite pattern observed at the encoding period of a specific item: more looking-at-nothing behaviour is needed to maintain spatial compared to verbal information. Taken together these findings point to a different oculomotor pattern during maintaining verbal compared to visuospatial information, which therefore suggests that eye movements have a weaker link with verbal memory maintenance compared to that with visuospatial memory maintenance.

1.2 Serial recall

Serial memory is the ability to store and retrieve novel sequences of items and events in the correct order. Serial memory is important for acquisition of vocabulary (e.g. Page & Norris, 2009), and motor skills (Agam et al., 2007; Baddeley, 2007), for communication through speaking (Dell et al., 1997), and typing (Logan, 2018). Serial memory is usually studied by presenting a list of verbal, visual, or spatial items which participants are then asked to recall in their original presentation order. One of the benchmark effects of serial recall is the serial position curve (for a review, see Hurlstone, in press), which consist of plotted recall accuracy values as a function of the serial positions of items. It is defined with a sharp monotonic decrease in recall accuracy from the first position onwards, known as the primacy effect, and a small increase for the final serial position, known as the recency effect. These effects have also been observed for visual-spatial locations (Avons, 2007; Farrand et al., 2001; Guérard & Tremblay, 2008; Tremblay et al., 2006). Another benchmark effect is that of temporal grouping, where differentiating a sequence into sub-groups has been shown to enhance recall accuracy and to produce effects of primacy and recency within each sub-group (Frankish, 1985, 1989; Hitch, 1996). Item similarity effects have been found for verbal, with phonologically similar sounding items recalled less accurately compared to phonologically dissimilar items (Baddeley, 1986), as well as for visual (Avons & Mason, 1999; Logie et al., 2016; Smyth et al., 2005), and spatial recall (Jalbert et al., 2008).

While the discussed research above is relating to forward serial order, recalling lists in backward direction, starting from the last presented item and finishing with the first presented item, alters the shape of the accuracy serial position curve. Performance in backward recall is generally worse than in forward recall, but this pattern is not consistently observed in visuospatial tasks (for a review, see Donolato et al., 2017). One way of attempting to explain processes in backward recall is the output interference account, which is included in the

Theory of Distributed Associative Memory (Lewandowsky & Murdock, 1989). It suggests that the crucial distinction between forward and backward recall lies in the number of events occurring between an item's presentation and its subsequent recall. For example, in backward recall the last presented item in the sequence does not have any intervening events before recall, while the first presented item in the sequence has a number of events equal to the number of the presented list with the addition of each of the responses until the first presented item is recalled. Another explanation was suggested by the peel-off-strategy (Conrad, 1965; Page & Norris, 1998), which posits that backward recall consists of a series of forward recalls. However, Norris et al., (2019) recently found that this strategy was rarely used in backward recall. Another model, which posits that backward recall requires more attention to order compared to item information, is the Scale Independent Memory Perceptual Learning model (Brown et al., 2007; Neath et al., 2014). More recently, Guitard and Saint-Aubin (2021) proposed the Encoding-Retrieval Matching Hypothesis, which suggests that backward recall of verbal information relies on visuospatial representations at retrieval. It also poses that the backward recall processes differ from forward recall as participants expecting a backward recall are more likely to encode visuospatial information. Indeed, research indicates that expectation of forward recall is associated with employment of phonological encoding strategies, leveraging auditory and verbal information (Guitard et al., 2020; Miles et al., 1991; Watkins et al., 2000).

However, it is still largely unclear what the underlying processes are in backward recall (Lewandowsky & Farrell, 2008). *Chapters 3 and 4* in this thesis aim to incorporate backward recall to both introduce conditions with increased cognitive load, as increased task difficulty should incentivise higher eye movement activity (Wynn et al., 2018), and also provide eye movement data to provide further insight into the strategies that might be used during forward and backward order recall.

1.3 Overview of current thesis

With the above considerations, this thesis aimed to explore gaze shifts when encoding and maintaining verbal or spatial information, what factors might influence these patterns, and whether specific gaze biases facilitate memory performance. *Chapter 2* explored how foreknowledge of recall order influences eye movements during presentation and retention of spatial and verbal materials. In *Chapter 3*, oculomotor activity during the visuospatial bootstrapping paradigm, which included the presentation of verbal information in either a familiar or a novel spatial layout, was investigated. Performance is suggested to be boosted for the familiar spatial layout, due to allowing long-term spatial representations to be utilised. The visuospatial bootstrapping paradigm therefore allows the exploration of differences in gaze shifts when long-term memory is utilised. *Chapter 4* involved a novel task which separated the presentation from the recall locations, allowing the disentanglement of gaze biases towards memorised and action-relevant locations. These chapters include, where relevant and possible, the fixation probability of interest areas across time for exploring how gaze shifts are influenced by the factors under investigation. Saccade amplitude also served as a general measure of oculomotor activity level, where a larger amplitude signifies a longer distance covered by a saccade from its beginning to end. This metric reflects how extensively the eyes move to capture visual information. The significance of measuring saccade amplitude lies in its ability to reveal the extent to which eye movements are involved in the encoding and maintenance of information and in preparing for actions. This distinction helps us understand how eye movements are used to process and retain visual information and to get ready for subsequent actions. Each of the studies in these chapters will be introduced briefly in the sections below and in more detail in the Introduction section of *Chapters 2 to 4*.

1.3.1 Foreknowledge of Recall Order

As previously mentioned, prior research identified differences in gaze behaviour during the encoding of verbal and spatial information (e.g. Czoschke et al., 2019). The patterns of eye movements during information encoding vary not only with the type of information but also with the context of the task (Yarbus, 1967). A notable similarity in eye movement patterns between encoding and retention phases is especially observed in more challenging task scenarios (Wynn et al., 2018). One aspect influencing encoding and retention strategies that has been identified is the foreknowledge of task demands (Guitard et al., 2020; Guitard & Saint-Aubin, 2021). However, it is not clear whether this influence of foreknowledge extends to variations in eye movement patterns specifically for verbal versus spatial information maintenance. *Chapter 2* aimed to explore potential differences in eye movement patterns during the maintenance of spatial and verbal information and how oculomotor activity is influenced by the predictability of the direction of recall order.

1.3.2 Long-term Memory

Previous research suggests that utilising long-term memory influences gaze patterns (e.g. Reingold & Charness, 2005; Van Der Gijp et al., 2017). Visuospatial bootstrapping (VSB) as described by Darling et al., (2017) and Darling and Havelka (2010), is the improvement in recalling verbal items when they are linked with significant visuospatial information from long-term memory. In their study, Darling and Havelka (2010) divided participants into three groups to recall digit sequences: one group viewed digits sequentially at the screen's centre, another saw digits highlighted on a typical ATM-style keypad, and a third group saw digits on a linear keypad display. The findings indicated that participants recalling digits using the typical keypad layout showed better verbal recall than those exposed to single digits or linear keypad layouts, with no notable recall difference between these latter two groups. This enhancement in memory, known as the VSB effect, occurs when long-term memory representations help in recall, surpassing conditions without such assistance. The current research aims to delve deeper into the visuospatial resources enabling the VSB effect, with a specific focus on understanding how eye movements shift across different VSB task conditions.

1.3.3 Separate Memory and Action Influences on Gaze

It is proposed that visual working memory is biased towards information relevant to actions, with its primary role being to facilitate goal-directed actions (for a review, see Heuer et al., 2020). Van Ede (2020) extended this view by highlighting the mutual influence between visual working memory and actions. Research has demonstrated that in dual-task scenarios, the content of visual working memory can involuntarily affect the path of saccades. Specifically, eye movements intended towards a goal tend to deviate from the position of an item simultaneously maintained in visual working memory while performing a secondary saccade-related task. (Belopolsky & Theeuwes, 2011; Boon et al., 2014; Theeuwes et al., 2005). Research examining eye movements without the influence of visual capture probes or secondary tasks has found that fixational eye movements naturally gravitate towards the remembered location of the chosen memory item (e.g. van Ede et al., 2019). While these findings suggest that eye movements during maintenance of information can be influenced by both memory and action preparation, the factors driving these biases in gaze direction are yet to be fully understood. *Chapter 4* aimed to provide a better understanding of the influences of memory and action on oculomotor behaviour when encoding and maintaining verbal and spatial information by separating the locations of where items are presented and recalled.

2 Memory and Foreknowledge: Eye Movements During the Encoding and Maintenance of Spatial and Verbal Information

2.1 Introduction

Working memory is a limited resource, allowing us to hold a handful of items in our mind at the same time (Cowan, 2001, 2010). The successful execution of many everyday tasks relies on the encoding, maintenance, and retrieval of relevant information. To safely navigate the world, we need to continuously keep in mind the locations of people and objects even (or especially) when they are no longer in our field of vision. Selecting relevant information derived from the sensory stream in our environment and in the internal space of memory is vital for interacting with a dynamic environment. Studies have shown that there is a tight link between visuospatial working memory and the oculomotor system during the encoding, maintenance, and retention periods (Heuer et al., 2020; Olivers & Roelfsema, 2020; Stigchel & Hollingworth, 2018). Eye movements are suggested to have a specific role for maintenance in visuospatial working memory (Baddeley, 1986; Morey, 2018; Pearson et al., 2014; Postle et al., 2006; Schut et al., 2017; Theeuwes et al., 2005, 2006; Tremblay et al., 2006).

Indeed, there is compelling evidence that the mechanics of eye movements themselves play a critical role in this interaction between the oculomotor system and memory. While covert attentional shifts have been found to interfere with spatial working memory, eye movements have been shown to interfere to a greater extent (Lawrence et al., 2004; Pearson & Sahraie, 2003). Additionally, looks to nonmemorized locations during the retention interval interfere with spatial memory (Hale et al., 1996; Postle et al., 2006).

Further, restricting eye movements during encoding has been suggested to impair memory performance (Damiano & Walther, 2019; Johansson et al., 2012; Laeng & Teodorescu, 2002; Richardson & Spivey, 2000). However, there are mixed findings regarding the degree of use and direction of eye movements during retention of visuospatial information. Eye movement patterns during the retention period have also been found to be correlated with eye movements during encoding of the image, with the similarity between those patterns suggested to predict performance (Laeng & Teodorescu, 2002; Olsen et al., 2014). However, other research argues against the idea that repeating an eye movement sequence facilitates memory (Foulsham & Kingstone, 2013; Johansson et al., 2012). Low oculomotor activity was also observed during the retention period of a spatial memory task (e.g. Pearson & Sahraie, 2003, Experiment 5).

Findings suggest that people tend to look towards empty locations which previously contained information that is now retrieved from memory (Altmann, 2004; Ferreira et al., 2008; Hoover & Richardson, 2008; Johansson et al., 2006; Richardson et al., 2009; Richardson & Spivey, 2000; Scholz et al., 2018; Spivey & Geng, 2001; van Ede et al., 2019). This phenomenon, termed looking-at-nothing (Ferreira et al., 2008; Richardson & Spivey, 2000; Scholz et al., 2018), has been found to have a functional role by facilitating memory retrieval of verbal and visuospatial information (Hollingworth, 2009; Laeng et al., 2014; Laeng & Teodorescu, 2002; Scholz et al., 2016), and serves as evidence that attention can be focused not only to perceptual information but also to information in the internal space of working memory. Tremblay et al. (2006) argue that the rehearsal of visuo-spatial information is achieved by eye movements, with some research suggesting that participants regularly look at the empty location where a memory item was previously presented (Altmann, 2004; Ferreira et al., 2008; Richardson & Spivey, 2000). More recently, in a series of experiments asking participants to recall the orientation or colour of bars, van Ede et al. (2019) revealed that selecting an item from memory produced a higher proportion of gaze shifts towards compared to away from the memorized location of the probed item, despite that spatial locations of the memory items were never probed. The degree to which participants need to engage with the items may be an important factor for oculomotor behaviour when selecting information from memory. Repetitive testing of the same pieces of information has been associated with diminishing looking-at-nothing behaviour (Scholz et al., 2011; Wantz et al., 2016), while when participants actively engage with information to make decisions or inferences, looking-at-nothing has been found to be stable (Jahn & Braatz, 2014; Scholz et al., 2015, 2017).

While a close relationship exists between eye movements and spatial memory, the link between eye movements and verbal memory seems to differ. In order to evaluate those links, it is important to consider how verbal information is maintained. Two different maintenance mechanisms have been identified: an articulatory mechanism, suggested to rely on processes similar to those of language production and to be verbal-information specific, and an attention-based mechanism, which is suggested to be domain-general, allowing maintenance of both visuospatial and verbal information (Camos et al., 2009; Camos & Barrouillet, 2014; Camos, 2015, 2017; Camos et al., 2011, 2013; Hudjetz & Oberauer, 2007; Mora & Camos, 2015; Mora & Camos, 2013; Rose et al., 2015; Vergauwe et al., 2014). While both of these mechanisms can be used jointly to maintain verbal information (Camos et al., 2009; Camos et al., 2011) they are suggested to be independent (Camos, 2015, 2017, for reviews; Camos et al., 2013; Mora & Camos, 2013). Each of the mechanisms has been suggested to be affected by different constraints: concurrent articulation can interfere with the articulatory mechanism as it depends on language processes (Baddeley et al., 1975; Baddeley, 1986), and concurrent tasks which distract attention impede the attention-based mechanism (see Barrouillet & Camos, 2015, for a review). Perhaps due to these two maintenance mechanisms and their suggested independence, verbal information maintenance may have a different link with eye movements. Indeed, attentional shifts have been suggested not to interfere with verbal working memory compared to spatial working memory (Lawrence et al., 2004). Moreover, eye movements to associated spatial locations did not help verbal memory retrieval more than shifting attention covertly (Scholz et al., 2018).

Recent research has delved into the differential impact of eye movements on the encoding and retrieval of verbal versus visuospatial information. In a study by Czoschke et al. (2019), participants were exposed to five bigrams displayed sequentially around a circular arrangement, each for a duration of one second without inter-item delays. The task required participants to recall and report the bigrams, their spatial positions, or both, in the sequence of presentation. The study observed a scarcity of saccades directed at items meant to be remembered during spatial task encoding, a trend not as pronounced in tasks involving verbal information. Indeed, this is supported by other studies which have found evidence for saccadic suppression during spatial compared to verbal memory encoding (Lange & Engbert, 2013; Patt et al., 2014). Interestingly, Czoschke et al. (2019) did not find a correlation between the fixation on specific items and subsequent memory performance. However, the researchers noted enhanced fixation on locations that had previously held items to be remembered by the end of the encoding phase, particularly in spatial and combined task conditions, in contrast to purely verbal tasks. This behaviour was significantly correlated with improved performance in spatial memory tasks, targeting primarily the location of the first item presented. This finding is supported by earlier observations by Lange and Engbert (2013) who found a distinction in the necessity of precise eye movements for encoding: verbal tasks demanded more focused eye movements towards items to be remembered than spatial tasks. Conversely, during the encoding of spatial information, a greater extent of "looking-at-nothing" behaviour was required, suggesting a more pronounced role of eye movements in the maintenance of spatial versus verbal information. Further evidence of this phenomenon comes from Staudte and Altmann (2017), who explored memory retention using a grid filled with letters. Participants were tasked with memorizing the location and identity of five highlighted letters sequentially. In a subsequent test, participants were asked to determine if a new sequence matched the one encoded, with the experiment manipulating whether a circle indicated object locations or alternatively whether letters were named verbally to denote identity without specifying locations. Analysis of eye movements preceding each test item's presentation revealed fewer eye movements towards locations that previously contained memory items in the verbal retrieval condition than in the location retrieval condition.

In addition to the type of information to be encoded, oculomotor patterns also vary depending on task context (Yarbus, 1967), with high similarity between eye movement patterns during the encoding and retention intervals found particularly for more difficult task contexts (Wynn et al., 2018). One factor that has been suggested to modulate the strategies employed for encoding and retention of information is foreknowledge (Guitard et al., 2020; Guitard & Saint-Aubin, 2021). Guitard et al. revealed that foreknowledge about the direction of recall (whether participants were forewarned about recalling information backwards or forwards) affected the detrimental impact of manual-spatial tapping on recall performance. Specifically, when the recall direction was known in advance, the negative effects of manual-spatial tapping were more pronounced in backward recall. However, when the recall direction was uncertain, the detrimental effects were similar for both forward and backward recall, indicating that predictability of recall direction modulates the impact of encoding strategies on recall performance. In contrast to these findings, earlier investigations indicated that foreknowledge did not significantly alter the impact of key memory factors on backward recall performance, suggesting a minimal moderating role of foreknowledge (Guérard &

Saint-Aubin, 2012; Li & Lewandowsky, 1993; Liu & Caplan, 2020). To reconcile the contradictory evidence regarding the influence of foreknowledge, the Encoding–Retrieval Matching hypothesis was proposed by Guitard and Saint-Aubin (2021). The hypothesis posits that the anticipation of recall direction, facilitated by foreknowledge, allows individuals to tailor their encoding strategies more effectively to the demands of the task. Specifically, it suggests that for backward recall, encoding strategies emphasizing visuospatial representations are more optimal, while forward recall benefits more from phonological representations. In the same vein, a review by Donolato et al. (2017) suggests that for verbal span tasks, backward recall is worse than forward order whereas for visuospatial tasks, backward recall is not always worse than forward recall. This differential encoding, enabled by foreknowledge, enhances the recall performance by ensuring that the features most suited for the anticipated recall direction are readily available during retrieval. In a recent study, Guitard and Saint-Aubin (2022) provided further support for the Encoding–Retrieval Matching hypothesis by demonstrating that the negative impact of manual-spatial tapping on recall was significantly greater for backward recall when the direction was predictable. Conversely, in conditions where the recall direction was unpredictable, the effect of manual-spatial tapping was equivalent across both recall directions, further underscoring the critical role of foreknowledge in shaping effective encoding strategies for backward recall. It remains unclear how predictability of the direction of recall order might influence eye movement patterns.

This present research aims to answer two main questions:

1. How does the type of information (spatial vs. verbal) affect oculomotor behaviour during encoding and recall phases?
2. What is the impact of recall order predictability on eye movements when encoding and maintaining information?

The current study aims to build upon Czoschke et al., (2019) by investigating potential differences in gaze shifts not only during the encoding but also the retention of spatial and verbal information. Further, it aims to investigate how eye movements are influenced by the predictability of the direction of recall order. Participants were eye-tracked during the presentation of four letters and during the presentation of four retro cues (which consisted of four numbers indicating either forward or shuffled recall order) and 2-second blank retention intervals after each retro cue. The shuffled recall order was included to remove any expectation of the recall order. Participants were asked to either recall the letters or the locations of the letters in the order indicated by the retro cues. Each retro cue affords the chance to discover whether gazes might indicate retrieval of the targeted item, and how this may occur differently in forward order, where the previous item itself might cue the next item, and in the shuffled order, where the cued item could come from any part of the list. This study also aims to extend the literature on how foreknowledge affects working memory by examining whether knowing the recall direction of items is associated with a different eye movement pattern, reflecting the idea posited by the Encoding-Retrieval Matching hypothesis (Guitard & Saint-Aubin, 2022) that knowing the direction of recall in advance enables individuals to adjust their encoding strategies more effectively to meet the task's requirements. Relatively few studies have examined gazes post encoding, and most that have used a long, free viewing period in which participants might look at any previous item in any order. This lack of restriction makes it difficult to use these data to discover systematic patterns. Differences in gaze patterns across conditions would indicate different involvement of the oculomotor system depending on the information type and predictability of recall order. These would provide further insight into which factors may be influencing eye movements reflecting oculomotor rehearsal or output preparation and whether specific gaze shifts facilitate performance.

2.2 Method

2.2.1.1 Participants

Twenty-one participants took part in the experiment, one participant was excluded from the analysis because the mean spatial accuracy was worse than 0.5 degree or a maximum spatial accuracy worse than 1 degree for each performed validation procedure, resulting in discarding 80 out of 1680 trials (4.76 %). The remaining 20 participants (5 male, 1 non-binary) ranged from 18 to 42 (M = 22.6, SD = 5.41). All participants were students at Cardiff University and were recruited via the School of Psychology's participant panel, social media and word of mouth. All participants reported normal or corrected-to-normal vision. The experiment was approved by the ethics committee of the School of Psychology at Cardiff University. No statistical methods were used to pre-determine sample size but the sample size was chosen to be similar to that of previous studies investigating similar measures ranging between 20 and 30 participants (e.g. Czoschke et al., 2019; van Ede et al., 2019).

2.2.1.2 Design, materials, and procedure

The task was administered using Experiment Builder (SR Research) on a screen monitor (width 53.2 cm; height: 30 cm; refresh rate: 60Hz) with a resolution of 1920 x 1080 pixels, viewed at a distance of 60 cm. Eye movements were recorded using a desk-mounted SR Research EyeLink 1000 Plus eye tracker with gaze position recorded at 1000Hz using pupil and corneal reflection, tracking both eyes of participants. A chin and forehead rest was used for head stabilisation. A 5-point calibration grid followed by a 5-point validation grid was used to fit and test the spatial accuracy of the eye tracker at the start of each block in the experiment. If validation showed a mean spatial accuracy worse than 0.5 degree or a maximum spatial accuracy worse than 1 degree, calibration and setup were repeated. The calibration and validation procedures were repeated if the pre-trial central point drift check error was above 1 degree for more than three successive trials.

The memory list consisted of 80 combinations of four letters, randomly drawn from [P, B, C, T, G, D, V]. Phonologically similar letters were chosen in an effort to bring verbal recall performance in line with spatial recall performance, because verbal recall with phonologically dissimilar letters or words is typically much higher than spatial recall with equivalent list lengths (Morey & Miron, 2016). Combinations which included CV, TV, GB, or PC were removed as they were deemed meaningful and new combinations were randomly generated. Four digits [1, 2, 3, 4] were used as retro cues in a random order. The letters and digits were presented in 40-point Times New Roman font, in upper case black font on mid-grey background (RGB: 153, 153, 153, 255). During the memory item presentation period, the position for each letter was randomised – there were two possible locations within a quadrant, with a letter presented in each of the quadrants during a trial. All possible memory item locations were approximately 10 visual degrees away from the centre of the screen. The recall contained either the 7 letters (in the order listed above) in a horizontal line in the middle of the screen approximately 5.5 visual degrees from one another, or 8 squares in the 8 possible memory item locations with a width and height of 62 pixels with a light-grey fill (192, 192, 192, 255) and a dark-grey outline (128, 128, 128, 255). The mouse cursor was a triangle 24 pixels wide and height of 19 pixels with a colour 192,192,192,255 and was present only during recall. The outline of 10 pixels on each side of a square with a width and height of 70 pixels was used to mark selected items or locations, with each selection triggering the outline in a different shade of grey.

Participants received both verbal and computerised instructions. They were instructed that they would be presented with four letters, presented one by one, followed by four digits which would refer to the sequential order in which either the letters or their locations would need to be recalled with a mouse click. Each trial began with a manual drift check followed by a blank screen for 500ms (see Figure 2.1 and Figure 2.2 for trial sequence). The first memory item was then presented stand-alone, which was then followed by the next three memory items. Each of these was shown for 1000ms and located in a different quadrant of the screen, in one of two possible locations within that quadrant (see Fig. 2.1 for illustration of the possible locations and trial sequence). After the final fourth memory item, a 500ms blank screen was presented for a clear demarcation of the end of the encoding phase. A list of four stand-alone retro cues (the digits 1, 2, 3, and 4) were then shown centrally each for 500ms, with a 2000ms blank display after each cue. The retro cues referred to each of the previously presented memory items, with the cues either indicating a forward order (indicating the same order as during the presentation period) or a new randomly shuffled order. The new shuffled order included all possible combinations excluding the forward order. Finally, depending on the condition, participants were asked to either recall the new order of the locations or the letters based on the retro cues. The screen for letter recall contained all possible letters in a fixed order in a horizontal line. The screen for location recall contained grey squares in all possible letter locations. Both recall screens contained the following instructions: “Click on the locations in the order indicated by the digit cues. If you cannot remember one of them, just guess.” or “Click on the letters in the order indicated by the digit clues. If you cannot remember one of them, just guess.”. These instructions were positioned on the top in the letter recall screen and in the middle of the location recall screen. Recall was achieved by a mouse click on four locations or four letters and no corrections were possible. There were 8 practice trials administered before the experiment and 80 experimental trials, presented in 4 blocks of 20 for each combination of recall condition (letter or location) and order condition (forward or shuffled) which were randomised across participants. The experiment took approximately 60 minutes to complete, and participants were given the opportunity to take breaks between blocks and trials.

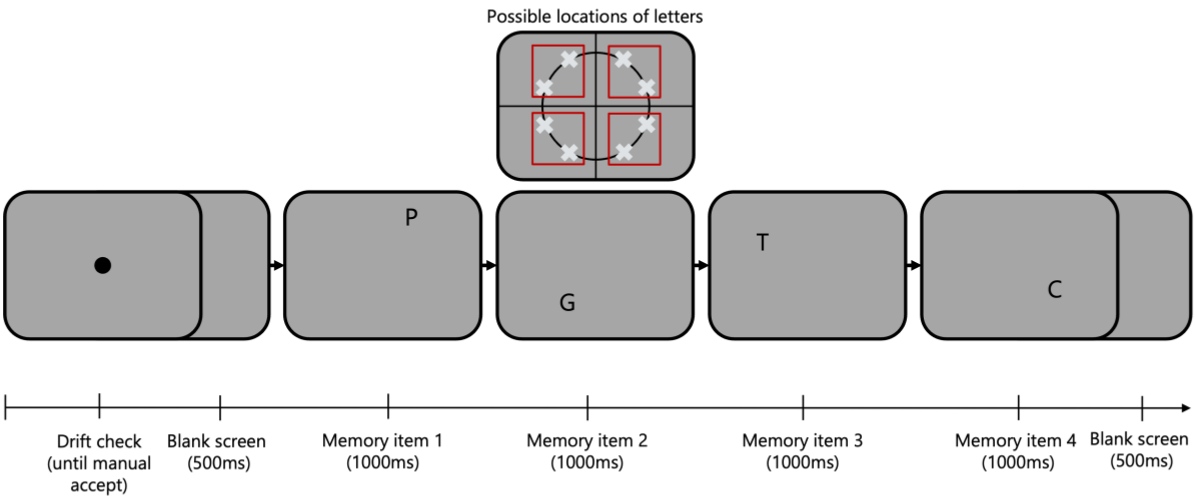

Figure 2.1 Illustration of encoding phase.

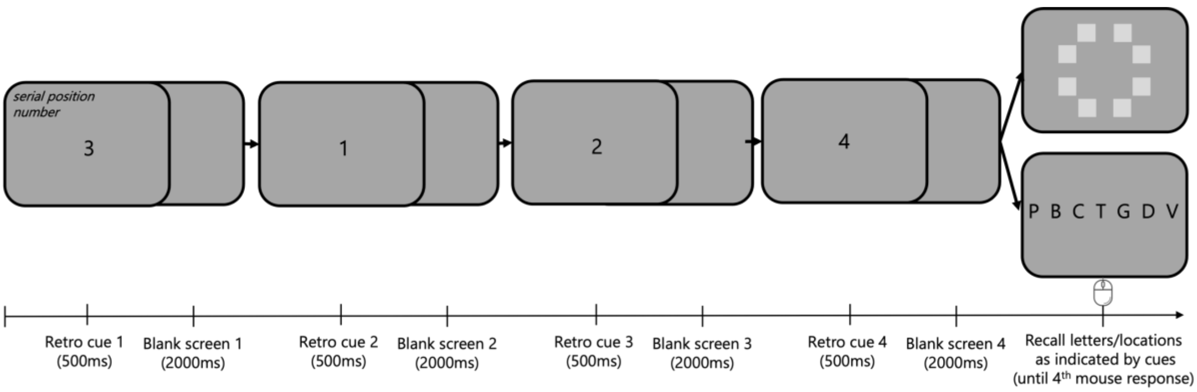

Figure 2.2 Illustration of shuffling and recall phases.

2.3 Results

2.3.1.1 Data Analysis

For analysis recall accuracy was arcsine transformed, while all eye movement measures were log-transformed in order to meet LMM assumptions. To investigate looking behaviour, four interest areas (IAs) were created with a size of 350 x 350 pixels in each quadrant, the centre of each being the middle between the two possible letter locations within a quadrant (shown in red in Figure 2.1) and calculated the proportion of looks to an IA based on the average position of samples from the left and right eye in intervals of 100ms. Beyond assessing performance accuracy, various eye movement metrics were also investigated. Saccade amplitude served as a general measure of oculomotor activity level, where a larger amplitude signifies a longer distance covered by a saccade from its beginning to end. The likelihood of fixating on the interest areas of displayed items and the chance of returning to previously memorized interest areas were used to determine the focus of oculomotor activity.

Analyses on recall accuracy and saccade amplitude were run using the lmer function of the lme4 package (Bates et al., 2015) in the R programming environment (The R Foundation for Statistical Computing, Version 4.3.2). Reported for each measure were the predictors' coefficients (*b* values), the *SE* values, *t* values, and the associated *p* values (generated using the lmerTest library for LMMs; Kuznetsova et al., 2017). Where effects approach but do not reach significance ($.05 < p < .1$) t and p values are reported, but not *b* or *SE* and no interpretative weight was put on such effects. In instances where the full model did not converge, indicating potential overparameterization or data sparsity issues, the model was systematically simplified by removing components in a stepwise manner until convergence was achieved. For such models, the random effects structure was first adjusted by constraining all covariance parameters to zero, and if estimation problems still persist then slope variables nearing zero are removed stepwise until the model converges (Bates et al., 2015). The final structure of the simplified model will be explicitly detailed.

Statistical evaluation of the gaze time courses was done with a cluster-based permutation approach (Maris & Oostenveld, 2007), which is suitable for assessing physiological effects across multiple data points such as eye movement data across time. In cluster-based permutation tests for eye-tracking samples, experimental conditions are compared using a simple statistic (e.g., t- or F-value). The process involves three steps: grouping samples with significant values into clusters, calculating cluster-level statistics by taking the sum of t-values within every cluster and generating a reference null-distribution through the Monte Carlo method which shuffles the mapping between condition labels and experimental data many times. By comparing the observed cluster to the reference distribution, the probability of obtaining the difference between conditions by chance is determined (Maris & Oostenveld, 2007). To integrate LMM into cluster analysis, the clusterperm.lmer function was utilised from the permutes package in R (Voeten, 2023). This function employs an algorithm that derives the null distribution by permuting data with regression models, including random effect structures using the Likelihood Ratio Test (LRT) (Lee & Braun, 2012). For each test 10,000 permutations were used, with a two-sided alpha level of .05. Consequently, the cluster-mass statistics in our data are derived from permuted LRT statistics. Additionally, a minimum cluster size of 100 was used as these were considered too small to be of interest. A larger cluster mass implies a more substantial effect or difference between the compared conditions across the cluster. It signifies that the observed differences are not just due to random chance but reflect a consistent pattern over the cluster's extent. Kendall's tau correlation analysis (Kendall, 1948) was selected to explore the relationship between trial accuracy and average fixation probabilities to the action interest area due to its suitability for ordinal data and its robustness against non-normal distributions. Unlike Pearson's correlation, which assumes linear relationships and normally distributed data, Kendall's tau is a non-parametric measure that assesses the strength and direction of association between two variables based on the ranks of data rather than the raw data values. This makes it ideal for handling datasets with ordinal or non-linear relationships.

2.3.1.2 Memory Accuracy

In order to consider the influence of recall and order conditions on recall accuracy, a Linear Mixed Model (LMM). The maximal model included trial accuracy as a dependent variable and recall condition (letter, location) and order condition (forward, shuffle) as categorical fixed factors. Participant was included as a random factor with random intercepts and slopes, and their interaction. The model resulted in a significant effect of order condition (b = .181, SE = .025, t = 7.10, p < .001), a non-significant effect of recall condition (t = -.37, p = .71) and a non-significant interaction (t = 1.88, p = .06). The results showed that trial recall accuracy was significantly higher in the forward conditions (M = .87, SD = .24) compared to shuffled conditions (M = .63, SD = .37; Figure 2.3). The absence of a significant main effect of recall condition suggests that using phonologically similar letters succeeded in roughly equating verbal recall and spatial recall. For a graph showing accuracy per response across conditions, please refer to Figure 1 in the Appendix.

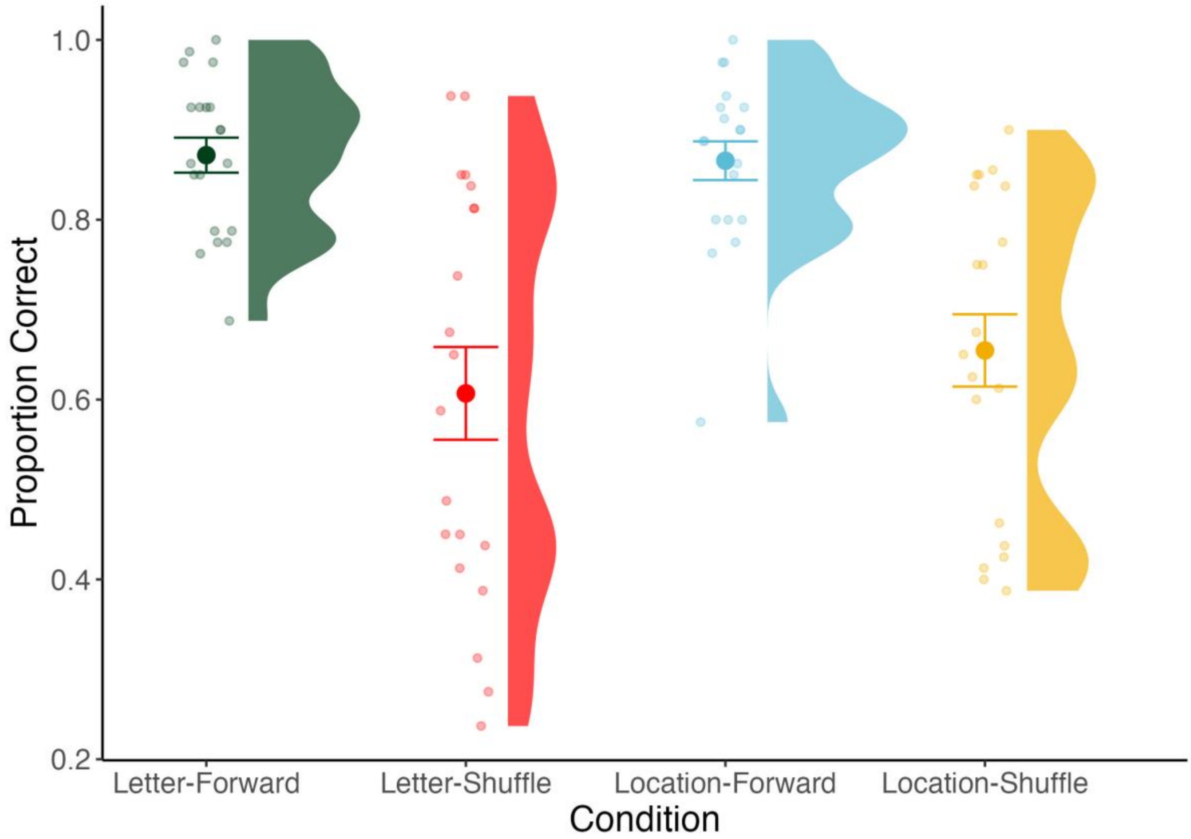

Figure 2.3 Mean proportion of trial accuracy for correct responses across conditions during the encoding and retro cue periods. Error bars show one standard error around the overall mean per condition. Points represent participant-specific means. Density curves along the continuous axis reveal data distribution and density across conditions.

2.3.1.3 Saccade Amplitude

In order to consider eye movement activity, two Linear Mixed Models were run, one focusing on the encoding period and another on the retro cue periods, to predict the average saccade amplitude per participant and per condition (illustrated in Figure 2.4) with fixed effects of the recall condition (letter or location) and order condition (forward or shuffle). For each participant, the model included random intercepts alongside random slopes for the interaction between recall condition and order condition.

During encoding, an overall effect of recall condition was found, $b = -.007$, $SE = .003$, $t = -2.11$, $p = .049$, with higher saccade amplitude in the location recall condition ($M = 7.62$, $SD = 1.63$) than in the letter recall condition ($M = 7.34$, $SD = 1.42$). The main effect of order did not reach significance ($t = 1.63$, $p = .12$), and the interaction between recall condition and order condition was not significant ($t = 0.33$, $p = .74$). This suggests that the average saccade amplitude significantly varies only across recall conditions (letter and location).

During the retro cue periods, there was an effect of recall condition ($b = -.033$, $SE = .015$, $t = -2.21$, $p = .039$), with higher saccade amplitude in the location recall condition ($M = 4.60$, $SD = 3.15$) compared to the letter recall condition ($M = 3.76$, $SD = 2.70$), and an effect of order condition ($b = .043$, $SE = .013$, $t = 3.28$, $p = .004$) with higher saccade amplitude in the forward order condition ($M = 4.74$, $SD = 3.27$) compared to the shuffle order condition ($M = 3.62$, $SD = 2.50$). The interaction between recall and order condition was not significant ($t = -.180$, $p = .86$).

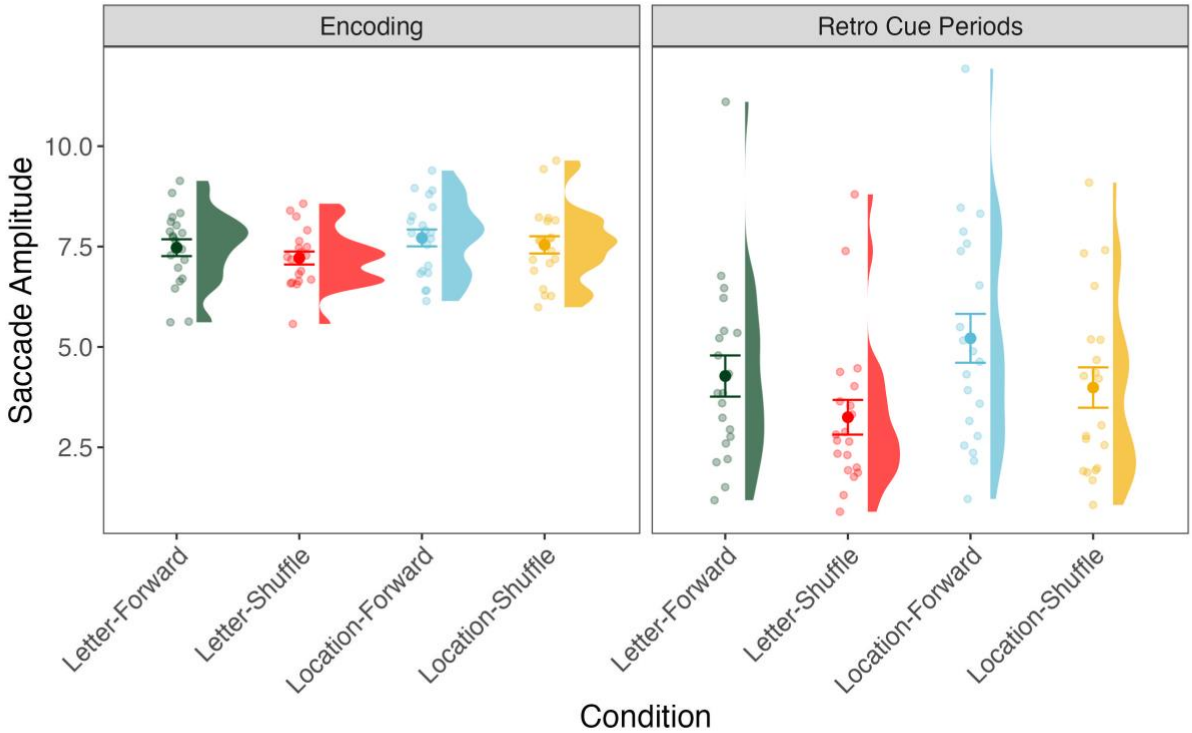

Figure 2.4 Mean saccade amplitude in visual degrees for each condition during the encoding and retro cue periods. Error bars show one standard error around the overall mean per condition. Points represent participant-specific means. Density curves along the continuous axis reveal data distribution and density across conditions.

2.3.1.4 Encoding Fixation Probability

Proportion of looks to presented items during encoding is illustrated in Figure 2.5. Proportion of looks to memory items was considered for each letter period rather than overall as for saccade amplitude, given that previous literature has indicated that this probability diminishes with each new item (e.g. Czoschke et al., 2019). The maximal model included fixation proportion as the dependent variable and recall condition (letter/location) and order condition (forward/shuffle) as categorical fixed factors. For each participant, the model included random intercepts alongside random slopes for the interaction between recall condition and order condition. The cluster-based permutation tests revealed a difference between the location and letter conditions: in the letter 3 period between 100-900ms (cluster mass =

346.92, $p < .001$), and in letter 4 period between 100-1000ms (cluster mass = 1020.89, $p < .001$). No significant differences between forward and shuffle conditions were found (no clusters were identified). Figure 2.6 focuses on the period of the presentation duration of the fourth letter in order to learn where participants looked (particularly in the location conditions) instead of at the presented item's location. In location recall conditions towards the end of the period looks are somewhat biased to the interest areas of the first and second presented letters.

Kendall's correlations were run to investigate the link between the overall pattern of looking at presented items averaged across the four encoding time periods and trial accuracy across all conditions, using the average values per participant and per trial. There was no correlation between the average fixation probability to presented items in the letter-forward condition and trial accuracy ($\tau = .11$, $p = .08$), and a weak negative correlation between the letter-shuffle condition and trial accuracy ($\tau = -.14$, $p = .008$). There was also a weak negative correlation between the average fixation probability to presented items in the location-forward condition and trial accuracy ($\tau = -.20$, $p < .001$), and a weak negative correlation between the location-shuffle condition and trial accuracy ($\tau = -.13$, $p < .001$).

Kendall's correlations were also run to investigate the link between fixation probability to the fourth item during its presentation period and accuracy for the same item, using the average values per participant and per trial. There was no correlation between looks to the fourth item in the letter-forward condition and accuracy for the fourth item ($\tau = -.04$, $p = .526$), and no correlation between fixation probability of the fourth item in the letter-shuffle condition and accuracy for the fourth item ($\tau = -.09$, $p = .096$). There were weak negative correlations between the fixation probability of fixating the fourth item and accuracy for the fourth item, both in the location-forward condition ($\tau = -.14$, $p = .002$) and the location-shuffle condition ($\tau = -.13$, $p = .005$).

Kendall's correlations were also run to investigate the link between cumulative probability of looks to previously presented items during the fourth letter presentation period (Figure 2.6; during which previous items were look at the most) and trial accuracy, using the average values per participant and per trial. There was no correlation between looks to previously presented letters in the letter-forward condition and trial accuracy (τ = -.08, *p* = .31), and no correlation between looks to previously presented letters in the letter-shuffle condition and trial accuracy (τ = -.03, *p* = .31). There were also no correlations between looks to previously presented letters and trial accuracy, both in the location-forward condition (τ = .04, *p* = .71) and the location-shuffle condition (τ = .08, *p* = .34).

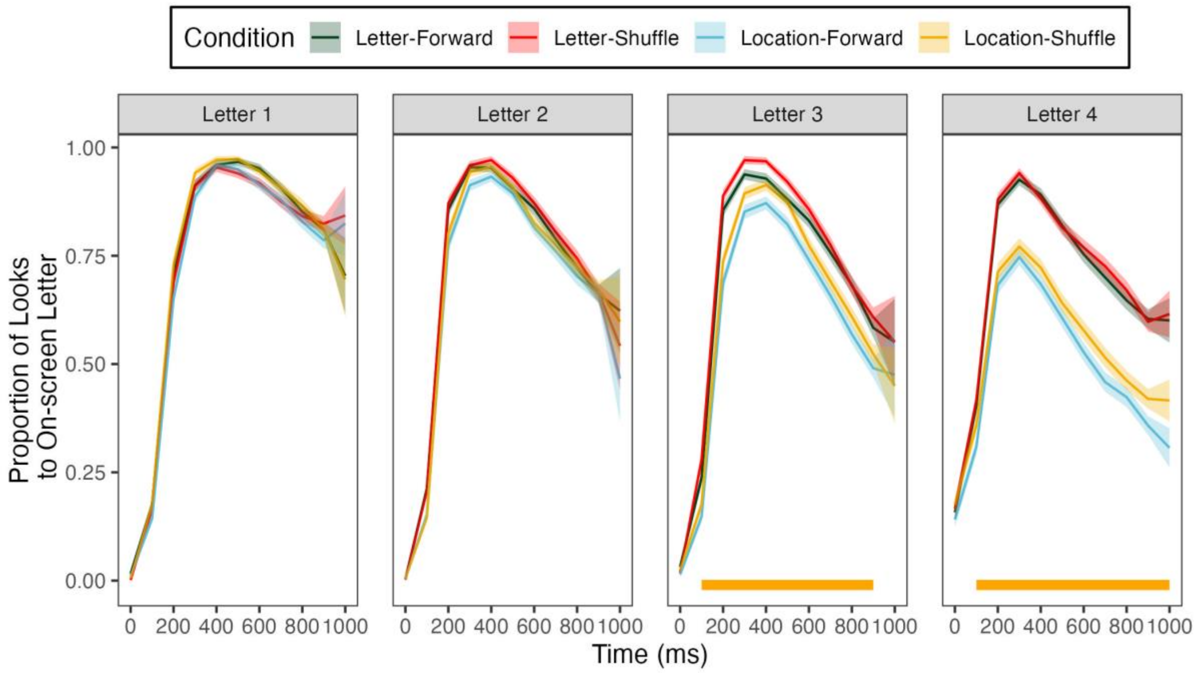

Figure 2.5 Mean fixation proportion of each of the on-screen letters over time for each condition. The orange line at the bottom (y = -.01) indicates significant clusters. Shaded areas represent within-participant standard errors around the mean calculated with the Cousineau-Morey method (Morey, 2008).

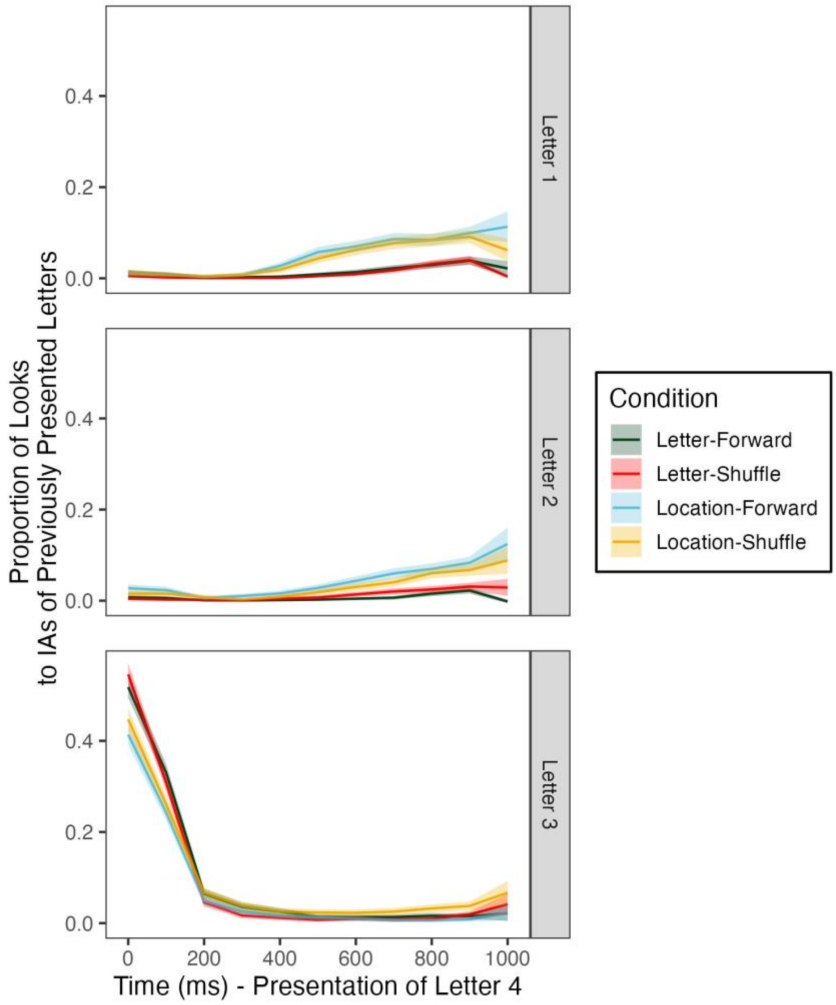

Figure 2.6 Mean fixation of the interest areas of the previously presented digits (1, 2, and 3) during the presentation of the fourth letter in each condition (letter-forward, letter-shuffle, location-forward, location-shuffle) across time. Shaded areas represent within-participant standard errors around the mean calculated with the Cousineau-Morey method.

2.3.1.5 Maintenance Fixation Probability

For each of the four retro cue periods, (consisting of the 500ms retro cue presentation display and a blank 2000ms display), gaze towards relevant cued items was plotted to investigate whether there is a bias towards the cued item (Figure 2.7A) as a function of condition (letter-forward, letter-shuffle, location-forward, and location-shuffle). Additionally, gaze patterns towards the first cued item were plotted (Figure 2.7B) to determine if eye movements are biased to the location of the first response throughout each retro cue period.

A cluster-based permutation test was run based on a LMM with proportion of fixating the relevant cued item interest area as the dependent variable and with recall condition (letter, location) and order condition (forward, shuffle) as fixed effects, and their interaction. For each participant, the model included random intercepts and random slopes for the interaction between recall and order condition. The start and end times, cluster mass, and p-values for each identified cluster are reported in Table 2.1. Overall, the results revealed higher proportion of looks to relevant cued item in the location compared to letter conditions across all periods. There was also a higher proportion of looks to relevant cued item in the shuffled compared to forward order. The same model but with proportion of looks to the first cued item as the dependent variable was run, with results reported in Table 2.2. Overall, the results revealed higher proportion of looks to first cued item in the location compared to letter conditions across all periods. There were also differences between the forward and shuffled order, but the direction of the effect was not consistent throughout the periods.

Kendall's correlations were run to investigate the link between the overall pattern of looking to the relevant cued item averaged across the four retro cue time periods and trial accuracy across all conditions, using the average values per participant and per trial. There was no correlation between the average fixation probability to relevant cued items in the letter-forward condition and trial accuracy (τ = -.001, p =.74), and no correlation between the letter-shuffle condition and trial accuracy (τ = -.015, p = .92). There was no correlation between the average fixation probability to relevant cued items in the location-forward condition and trial accuracy (τ = .072, p = .62), and a weak positive correlation between the location-shuffle condition and trial accuracy (τ = .14, p = .001).

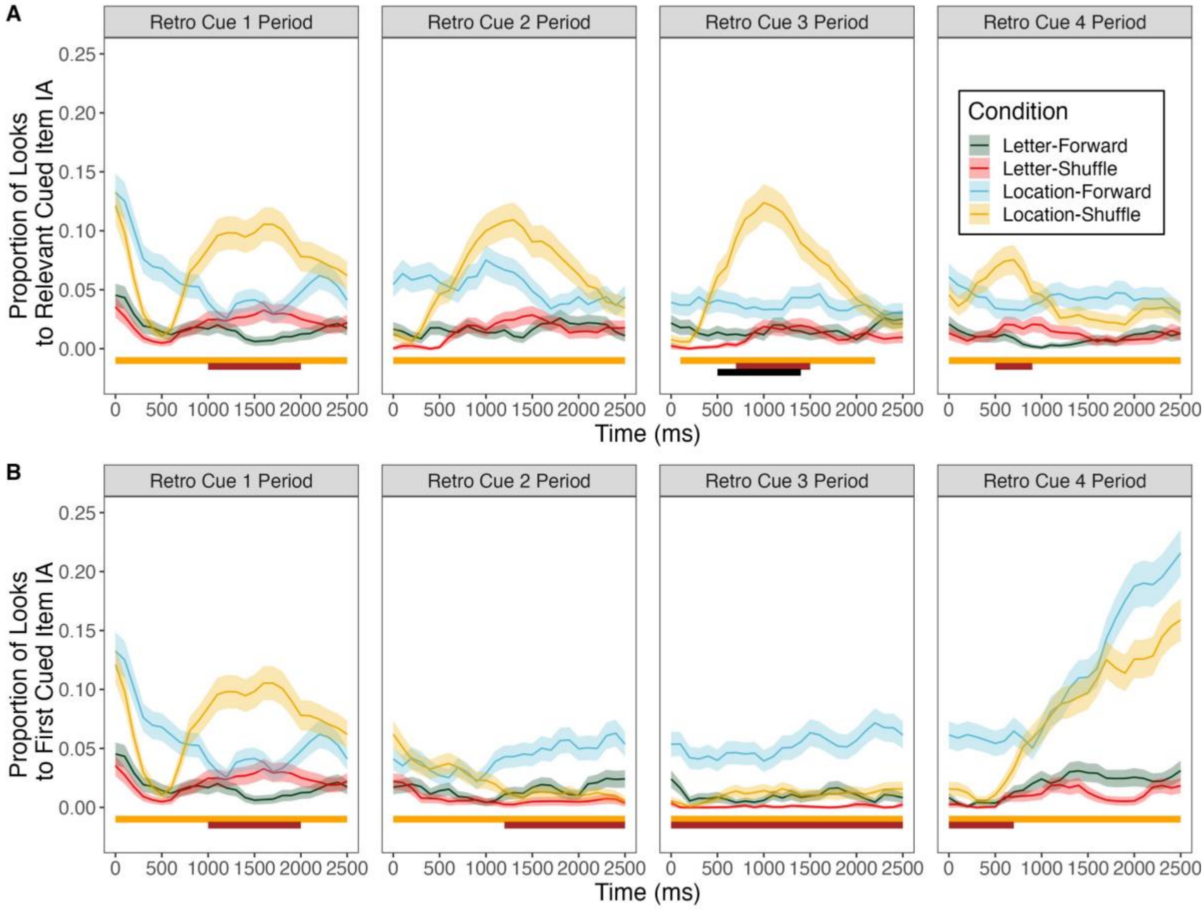

Figure 2.7 Cluster-based permutation test on each of the four retro cue periods for the fixation probability of A) the relevant cued item IA and B) the first cued item across location and letter recall conditions. Note that the retro cue is displayed from 0ms to 500ms. Horizonal lines at the bottom (y = -.01; -.15) denote significant cluster differences: orange illustrates the difference between the letter and location recall conditions; brown illustrates the difference between shuffle and forward recall conditions; black shows their interaction. Shaded areas represent within-participant standard errors around the mean calculated with the Cousineau-Morey method.

Table 2.1

*Cluster-Based Permutation Analysis (CPA) based on model: Proportion of Looks to Relevant Cued IA ~ Recall * Order + (1 + Recall * Order | Participant)*

Interest Period	Condition/parameter	Time Start	Time End	Cluster Mass	*p*
Retro Cue 1 Period	Recall (letter vs location)	0	2500	685.05	< .001***
	Order (forward vs shuffle)	1000	2000	184.95	< .001***
Retro Cue 2 Period	Recall (letter vs location)	0	2500	654.47	< .001***
Retro Cue 3 Period	Recall (letter vs location)	100	2200	592.50	< .001***
	Order (forward vs shuffle)	700	1500	132.67	< .001***
	Interaction	500	1400	141.01	< .001***
	Location Only (forward vs shuffle)	600	1500	174.60	< .001***
Retro Cue 4 Period	Recall (letter vs location)	0	2500	453.99	< .001***
	Order (forward vs shuffle)	500	900	37.60	< .001***

Note. * $p < .05$, ** $p < .01$, *** $p < .001$

Table 2.2

*Cluster-Based Permutation Analysis (CPA) based on model: Proportion of Looks to First Cued IA ~ Recall * Order + (1 + Recall * Order | Participant)*

Interest Period	Condition/parameter	Time Start	Time End	Cluster Mass	*p*
Retro Cue 1 Period	Recall (letter vs location)	0	2500	685.05	< .001***
	Order (forward vs shuffle)	1000	2000	184.95	< .001***
Retro Cue 2 Period	Recall (letter vs location)	0	2500	279.93	< .001***
	Order (forward vs shuffle)	1200	2500	220.92	< .001***
Retro Cue 3 Period	Recall (letter vs location)	0	2500	480.15	< .001***
	Order (forward vs shuffle)	0	2500	443.81	< .001***
Retro Cue 4 Period	Recall (letter vs location)	0	2500	1,559.28	< .001***
	Order (forward vs shuffle)	0	700	113.02	< .001***

Note. * p < .05, ** p < .01, *** p < .001

2.4 Discussion

The study aimed to investigated gaze during the encoding and maintenance of verbal and spatial information either in a predictable forward or an unpredictable shuffled order. Results clearly demonstrate that the type of information to be recalled and the recall order influence gaze shifts.

A higher recall accuracy was found in forward order as opposed to shuffled order conditions for both spatial and verbal information. This contrasts with previous research which suggests that backward recall is associated with a decrease in performance in verbal span tasks whereas for visuospatial tasks, backward recall is not always worse than forward recall (Donolato et al., 2017, for a review). The presence of a significant difference between order conditions for verbal information in the current study could also be because the shuffled order is more demanding and less predictable compared to backward order. In the shuffled order condition, participants must attend to each retro cue to find out the order in which they need to report items. The findings from the current study identify foreknowledge of the recall order as an important factor affecting performance.

During encoding, higher saccade amplitude were observed in the location compared to the letter recall condition, suggesting that participants looked around more in the location recall conditions. Analysis of the encoding period indicated that there was a significantly higher probability of looking at on-screen letters in the letter compared to the location recall conditions during the presentation of the third and fourth letter. These findings suggest that encoding verbal information is associated with more precise looks to the interest areas of the presented letters, while for spatial encoding looks are increasingly biased away from the presented letters. Indeed, a closer investigation of the presentation period of the last letter suggests that these looks are somewhat biased to the interest areas of the first and second presented letters, suggesting that locations of previously presented items are revisited during spatial recall. These findings are in line with previous research which has found diminished looking directly at items during spatial compared to verbal task encoding (Czoschke et al., 2019; Lange & Engbert, 2013; Patt et al., 2014). Weak negative correlations were found between trial accuracy and probability of looking at the on-screen item in all conditions apart from the letter-forward condition, suggesting that a higher proportion of looks to the presented item is associated with a *decrease* in performance. This could indicate that instead of looking at the on-screen item, regressions to the locations of previously-presented items might be an important strategy for correctly recalling items. This view is supported by Czoschke et al. (2019), who found in their study that increased fixations to locations of previously presented items during encoding (rather than fixating what was currently presented) was associated with enhanced performance. However, in this study we failed to find a clear link between previously presented items during encoding and accuracy, which suggests that this strategy may not be consistently employed and that looking behaviour does not clearly influence memory performance.

During the four retro cue periods which included each retro cue followed by a blank display, a higher saccade amplitude was found in the location compared to the letter recall condition, and higher amplitudes in the forward order compared to the shuffle order condition. Analysis of the time course of proportion of looks to the relevant cued interest areas showed significantly higher values in the location conditions compared to the letter conditions throughout all time periods. Interestingly, despite more oculomotor activity observed in the location-forward condition, the location-shuffle condition had a more pronounced proportion of looks towards the relevant cued interest area. These findings suggest that eye movements are strategically directed to locations that previously contained the relevant cued item only when recalling spatial information, and that this is most clearly seen in the condition where the recall order is not predicable from the beginning. Indeed, it could be that the additional complexity of remembering not only the presented list but also the new order sequence in the shuffle condition requires the recruitment of oculomotor rehearsal. Evidence for this view also comes from the weak positive correlation found between trial accuracy and proportion of looks to the relevant cued item in the location-shuffle condition. These findings are in line with the view that more revisits of memorised locations occur in spatial compared to verbal recall tasks (Czoschke et al., 2019; Lange & Engbert, 2013; Patt et al., 2014). Indeed, visuospatial working memory is thought to be more dependent on executive resources compared to verbal working memory, with evidence suggesting that dual-task interference impacts visuospatial more than verbal memory (e.g., Morey, 2018).

The pronounced probability of looks to relevant items in the location-shuffle condition is also consistent with research suggesting that revisiting of memorised locations is stable when participants actively engage with information (Jahn & Braatz, 2014; Scholz et al., 2015, 2017). This finding also suggests greater reliance on visuospatial working memory in shuffled order compared to forward order in spatial recall, which adds important insights to the literature investigating the forward and backward order and the different reliance on verbal and spatial representations (e.g. Donolato et al., 2017). Interestingly, a difference was found between forward and shuffle order conditions in oculomotor activity during retention and and no difference was found in encoding strategies between the order conditions. While research suggests that anticipating the order of recall should allow tailored encoding strategies (Guitard & Saint-Aubin, 2021), in the current study it was found that oculomotor activity fails to provide evidence for different encoding strategies, and instead points to the maintenance period as being able to indicate the use of different strategies. However, in shuffle order the recall order was not finalised until the presentaton of the last item, requiring participants to actively engage with each of the memory items, which differs from backward order where participants know the direction as soon as the direction is specified. It might be that backward and shuffle order tasks involve different encoding strategies and perhaps unique gaze patterns. It also investigated if eye movements are biased to the location of the first cued item throughout each retro cue period, which would indicate either oculomotor rehearsal attempts starting from the beginning of the newly set order or a preparation for the first response. A higher proportion of looks was found to the first cued item for the location compared to the letter recall conditions, with the most pronounced probability of looks in the location-forward condition. This suggests that when recalling spatial information with foreknowledge of the order in which it needs to be recalled, participants are biased towards the first cued item. The highest values were observed during the final retro cue period, reflecting either a rehearsal of or output preparation for the first cued item.

Overall, the current study aimed to expand on previous work on oculomotor activity for verbal and spatial information (e.g. Czoschke et al., 2019) by investigating both the encoding and the maintenance periods and the influence of foreknowledge of the recall order. A decreased proportion of looks to on-screen item during encoding was replicated and an increased looking to relevant cued items was found during retention when recalling spatial compared to verbal information, which was specifically pronounced in unpredictable shuffle order. The findings from the current study are in line with research supporting the view that looks are biased towards memorised spaces (e.g Tremblay et al., 2006; van Ede et al., 2019) but they also point to strategic looks dependent on the type of information to be recalled and foreknowledge of the recall order.

3 Navigating the Mind's Eye: Understanding Gaze Shifts in Visuospatial Bootstrapping

3.1 Introduction

Working memory (WM) is a limited capacity system which allows the storing and manipulation of information, and which is suggested to require an active rehearsal process to prevent forgetting (Baddeley et al., 2021; Barrouillet & Camos, 2021; Cowan et al., 2021). A common assumption among leading theoretical approaches is for a flexible interplay between visual, verbal, and spatial information, pulling in influences of prior knowledge from long-term memory. The extent to which these are involved in any given situation is likely to depend on task context. Investigating the contributions of these components to task performance and attention is important for better understanding working memory and how it can be enhanced.

Visuospatial bootstrapping (VSB; Darling et al., 2017; Darling & Havelka, 2010) refers to a recall benefit arising from the association of verbal items with meaningful visuospatial information stored in long-term memory. Darling and Havelka (2010) investigated the recall of sequences of digits of three groups of participants. One group was presented with the digits one-by-one in the middle of the screen, another group was presented with a typical numerical keypad (as on an ATM) with each number from the sequence being highlighted one by one, while the third group was presented with a display containing a linear keypad. The authors found that verbal recall of the sequence was higher in the group which was presented with a typical keypad compared to the single digit or linear keypad displays, and the difference between the latter was revealed not to be significant. The VSB effect refers to this memory benefit observed when long-term representations are utilised to aid recall over the absence of such a pattern.

The VSB benefit has been reliably replicated (Allan et al., 2017; Allen et al., 2015, 2023; Calia et al., 2015; Darling et al., 2012, 2014; Darling & Havelka, 2010; Race et al., 2015, 2023) and investigated further to better identify its source. Darling et al. (2012) presented participants with sequences of digits in four different display types. They included the single digit and typical keypad displays mentioned above, and introduced a novel static keypad and a novel changing keypad which included a display similar to the typical keypad but containing rearranged digits that were not in their typical location. In the static condition the location of the digits did not change, whereas they did so with every display in the novel changing condition. Recall of the digit sequences was higher again in the typical keypad condition compared to the other conditions, with no significant difference between the other three conditions. It is noteworthy that recall improved in the later trials of the novel static keypad condition suggesting that new arrays can be learned. The authors suggested that the early disadvantage in the novel static keypad condition could be attributed to overcoming the interference of the long-term knowledge pattern of the typical keypad. Darling et al. (2012) suggested that these findings indicated that the long-term knowledge of the locations associated with specific digits enable the integration of visuospatial and verbal information. Further, developmental research supports this view of long-term knowledge playing an important role in VSB. The VSB effect has been investigated in 6-year-old and 9-year-old children, young adults (Darling et al., 2014), as well as in older adults (Calia et al., 2015), with the effect observed in every group with the exception of the 6-year-old children. The absence of the benefit in young children could be attributed to the lack of sufficient accumulation of typical keypad pattern knowledge, which further provides evidence for the dependence of VSB on accessing long-term representations. Taken together, these findings have been suggested to support the view that long-term memory for the visuospatial layout is essential for the VSB effect.

Several lines of research have also contributed important findings that illuminate what mechanisms contribute to this phenomenon. Allen et al. (2015) introduced articulatory suppression during the encoding phase of the VSB paradigm and found that it resulted in disruption of recall to a greater extent when digits were presented in a single location compared to when presented in a typical keypad display. This finding suggests that performance in the single digit condition is more heavily dependent on verbal maintenance as it does not contain additional environmental cues, whereas in the keypad condition the familiar spatial pattern could reduce the reliance on verbal working memory. Further, Allen et al. (2015) used concurrent spatial tapping either at encoding or at retrieval during an immediate serial recall task, as well as during retention during a delayed recall task with a 5-second retention period (Allen et al., 2023). The VSB effect was not observed when the spatial tapping occurred during encoding or retention in a delayed recall task but was present if the spatial tapping only occurred at retrieval. This finding suggests that the integration of knowledge occurs at encoding. In another study, Allan et al. (2017) manipulated the path complexity of sequences to examine if the quality of spatial representations also play a role in the VSB, alongside the familiarity of the keypad layout. While they observed effects of both path complexity and VSB, these did not interact. The presence of the path complexity effect has been suggested to show that incidental encoding of spatial path occurs in verbal memory tasks, regardless of the layout familiarity. Allan et al. also analysed recall accuracy by serial position and revealed that the VSB effect specifically boosted memory for items towards the end of the lists. Darling et al. (2020) demonstrated a VSB effect with novel non-words which were presented either in a changing or unchanging layout, with the static one allowing the building up of location knowledge. They found that reliable spatial information facilitated sequence learning, especially later in the sequence. The authors suggested that the incidental availability of spatialized information during encoding can facilitate not only recall of digits, but also nonwords. The findings also suggest that the spatial information can be learned during the task itself and does not depend on already familiar long-term patterns. Alongside long-term acquisition of the boot-strapped knowledge, visuo-spatial resources are specifically implicated in the use of that knowledge when encoding and briefly maintaining verbal lists.

The present investigation aimed to provide further detail about the characteristics of the visuo-spatial resources that support the VSB effect. An unknown factor is how gaze shifts during the conditions of the VSB task. Research shows that people tend to look towards empty locations which previously contained information that is now retrieved from memory (Altmann, 2004; Ferreira et al., 2008; Hoover & Richardson, 2008; Johansson et al., 2006; Richardson et al., 2009; Richardson & Spivey, 2000; Scholz et al., 2018; Spivey & Geng, 2001; van Ede et al., 2019). This phenomenon, known as looking-at-nothing (Ferreira et al., 2008; Richardson & Spivey, 2000; Scholz et al., 2018), has been found to have a functional role by facilitating retrieval of both verbal and visuospatial information (Hollingworth, 2009; Laeng et al., 2014; Laeng & Teodorescu, 2002; Scholz et al., 2016). While covert attentional shifts have been found to interfere with spatial working memory, eye movements have been shown to interfere to a greater extent (Lawrence et al., 2004; Pearson & Sahraie, 2003), which is consistent with the position that movement entails spatial attention but spatial attention does not necessarily require movement (Smyth, 1996). Altogether, this evidence points to oculomotor activity as a potential supporting factor that might underlie the VSB advantage.

Eye movements have been surmised to play a specific role for maintenance in visuospatial working memory (Baddeley, 1986; Morey, 2018; Pearson et al., 2014; Postle et al., 2006; Schut et al., 2017; Theeuwes et al., 2005, 2006; Tremblay et al., 2006), but as yet it remains unclear how and when they may support recall in a serial spatial working memory task. Looking to nonmemorized locations during the retention interval interferes with spatial memory (Hale et al., 1996; Postle et al., 2006), supporting the view that there is a tight link between eye movements and spatial memory maintenance. With serial presentation, maintenance processes begin during the presentation of subsequent list items, and as incoming information is presented for later recall, distinct gaze patterns emerge when spatial position is to-be-remembered, as opposed to identity. Czoschke et al. (2019; see also Lange & Engbert, 2013) observed that during the encoding of verbal information, participants made precise eye movements to to-be-remembered items, contrasting with spatial information encoding, where such saccades were scarce. At the end of the encoding period, pronounced fixations to locations that previously contained to-be-remembered items were linked with increased spatial memory performance, indicating more looking-at-nothing behaviour for maintaining spatial as opposed to verbal information. This pattern is supported further by Staudte and Altmann, (2017), who found fewer eye movements towards locations that previously contained memory items during the identity (verbal) retrieval condition compared to the location retrieval condition. These findings highlight a distinct oculomotor pattern during encoding and maintenance of verbal information versus visuospatial information.

However, while these patterns may occur consistently, whether they support recall accuracy in a meaningful way is less clear. Lower oculomotor activity is often observed during the retention period of a spatial memory task (e.g., Pearson & Sahraie, 2003, Experiment 5; Morey et al., 2018), which is unexpected if eye movements or oculomotor planning make a robust contribution to maintaining locations. Placeholders for remembered locations increase spontaneous eye movements during retention (Loaiza & Souza, 2022), which does not seem wholly consistent with the idea that eye movements are actively used for maintenance. Even when spontaneous eye movements are observed during retention, their utility is not clear. Loaiza and Souza found no correspondence between looking at the location of a to-be-remembered item and recall precision. In contrast to these findings, Tremblay et al. (2006) and Morey et al. (2018) found that spatial serial reconstruction accuracy increased when participants fixated elements of the list in order during retention. However, in both investigations, participants engaged in quite limited amounts of ordered looking despite having a free interval of several seconds. Altogether, this body of evidence suggests that looking back towards previously presented locations might modestly strengthen memory for a small subset of them, which makes support from gaze a plausible contributor to the VSB effect.

This study aims to answer the following main question:

- Is there a difference between eye movement patterns when encoding and retaining verbal information with a familiar versus a novel spatial layout?

In two experiments, gaze was investigated during a VSB task. In Experiment 1, participants were eye-tracked during presentation of seven digits shown in three configurations (familiar telephone keypad, dynamic randomised novel keypad, and centrally presented single digit) and during a 5-second retention interval. The 5-second retention period was imposed between the end of list presentation and opportunity to recall to learn whether participants use free time to fixate the encoded positions of to-be-remembered digits. During this retention period an empty keypad grid was presented in the typical and novel-changing keypad conditions, and a blank display in the central condition. In Experiment 2, retro cues were incorporated in a VSB paradigm to allow for clearer interpretation of eye movements and included both forward and backward recall to investigate if the VSB effect can be observed in backward recall. Differences in performance would reflect contributions from the presence of a spatial layout. If the visuo-spatial bootstrapping advantage occurs because of domain-specific spatial encoding, then deviations may be seen in the patterns of eye movements made to familiar keypads where the spatial layout confers information about the to-be-remembered digits compared to random arrangements where the spatial locations provide no relevant clues.

3.2 Experiment 1

3.2.1 Method

3.2.1.1 Participants

Forty-one participants took part in the experiment. Three participants were excluded due to poor eye tracking calibration and validation values (the mean spatial accuracy was worse than 0.5 degree or a maximum spatial accuracy worse than 1 degree for each performed validation procedure). The 38 remaining participants (14 male) ranged from 19 to 40 (*M*= 24.53; *SD*= 5.31). All participants were students at Cardiff University and were recruited via the School of Psychology's participant panel, social media and word of mouth. All had normal or corrected-to-normal vision.

3.2.1.2 Design, materials, and procedure

The task was administered using OpenSesame (Mathôt et al., 2012) on a display monitor with a resolution of 1024x768 pixels (width 53.2 cm; height: 30 cm; refresh rate 60Hz), viewed at a distance of 60 cm. Eye movements were recorded using a desk-mounted SR Research EyeLink 1000 Plus eye tracker which recorded monocular eye movements at 1000Hz using pupil and corneal reflection tracking. Fixations were detected using the standard SR Research algorithm. Participants were tested individually in a dimly illuminated room. Participants completed three practice trials, one per display condition, before beginning the experiment. They were given the opportunity to ask questions before beginning the experimental procedure. A 5-point calibration grid, followed by a 5-point validation grid was used to fit and test the spatial accuracy of the eye-tracker at the start of experiment. If validation showed a mean spatial accuracy worse than 1 visual degree or a maximum spatial accuracy worse than 2 visual degrees, calibration and setup were repeated. Each trial began with a drift check (a central point which the participant had to fixate) that was manually accepted by the researcher, and if both eyes had an error of more than 0.5 degree, then the calibration and validation procedure was repeated. Participants completed 6 randomly ordered blocks of 8 trials each, 2 blocks per display condition (48 trials in total). Both the blocks and the trials within the block were randomised.

To-be-remembered 7-digit lists were randomly determined at run time, selected from the set {0, 1, 2, 3, 4, 5, 6, 7, 8, 9} without replacement. In all conditions, a white 3 x 3 x 3 + 1-cell grid resembling the layout of a telephone number pad was presented onscreen, against a dark grey background (#2E3436). Each cell in the grid measured 60x60 pixels, separated by 130 pixels from centre to centre. In the typical keypad display, digits were arranged as they would be found on a telephone keypad. In the novel-changing display, digits were allotted to grid cells randomly on each trial. In the central display, each digit of the 7-item list appeared successively in the middle cell of the grid (i.e., where 5 would be in the typical keypad). Because the cells in the central display condition do not have contextual meaning, gaze analyses that aim to determine whether looking benefited accuracy contrast the typical keypad and novel-changing display only. Responses from the central display condition were included in descriptive accuracy analyses to illustrate the expected boosts to performance with typical keypad displays and the expected detriments with the novel-changing display in comparison with the central display. An initial analysis of saccade amplitude was also included across all three layout conditions to confirm that participants look around much less in the central display condition.

Each trial began by presenting 7 digits visually, one by one, each for 800ms with an interitem interval of 400ms after each digit, which contains an empty keypad grid for all conditions. The digits were presented in black font Droid Sans Mono with a size 18. For the single digit condition, each digit was presented in the middle of the screen, while for the typical and novel keypad displays, all digits (0-9) were presented in a keypad layout, with digits positioned in a 3 x 3 +1 matrix and the relevant digit being highlighted by changing the colour of its background to blue (#0000FF). After the final digit in the list was presented (including the 400-ms unlit display), all numbers disappeared from the grid and the blank grid remained onscreen for 5000ms. Finally, participants saw a prompt to recall the digits orally in order and the researcher typed in each response spoken by the participant. No changes to the response were allowed, but participants were allowed to indicate if they did not know a position by saying “blank” instead of a digit. After completing each 8-trial block, the participant was offered a break.

3.2.2 Results

3.2.2.1 Data Analysis

A Bayesian Analysis of Variance (Rouder et al., 2009, 2012) was conducted with the default settings of the BayesFactor package (Morey et al., 2022). This was implemented in R studio (R Core Team, 2013). The Bayes Factor (*BF*) is the relative likelihood of two models given the data, with models with highest *BF* value being preferred by the data and referred to as the best models. Null models contain only between-subject variance. By taking the ratio of the best model and other models that omit or include a given effect, evidence for or against including a predictor can be computed. For interpretation, guidelines established by Lee & Wagenmakers (2014) were used where a *BF* of 3-10 represents moderate evidence in favour of the alternative hypothesis, and a *BF* of over 10 represents strong evidence. In addition to performance accuracy, several eye movement measures were considered. Saccade amplitude was taken as a broad indication of the amount of oculomotor activity, with higher amplitude indicating a greater distance from the start to the end of a saccade. The probability of fixating the interest areas of presented items and the probability of revisiting memorized interest areas were taken as indicators of where oculomotor activity was directed. For analysis recall accuracy was arcsine transformed, while all eye movement measures were log-transformed. Kendall's tau correlation analysis (Kendall, 1948) was selected to explore the relationship between trial accuracy and average fixation probabilities to the action interest area due to its suitability for ordinal data and its robustness against non-normal distributions. Unlike Pearson's correlation, which assumes linear relationships and normally distributed data, Kendall's tau is a non-parametric measure that assesses the strength and direction of association between two variables based on the ranks of data rather than the raw data values. This makes it ideal for handling datasets with ordinal or non-linear relationships.

3.2.2.2 Recall Accuracy

Figure 3.1 shows the recall accuracy as a function of layout (central, novel-changing keypad, and typical keypad) and serial position (1-7). For consistency with the gaze analyses reported below, which sometimes also include accuracy of recall as a factor, this inferential analysis contrasts the typical and random keypad conditions.[1] The best model of this data included the main effects of serial position and layout $BF = 1.59 \times 10^{48}$. The best model was preferred over a model including only the main effect of serial position by BF of 3.64, and over the full model including the main effects and their interaction by BF of 85.69. The best model was

[1] The same model was run including the central condition and the best model for the data included only a main effect of serial position.

also favoured over a model including only the main effect of layout by a *BF* of 1.82 x 10^{48}. Although this boot-strapping advantage appears rather small, recall was improved in the typical compared to the novel-changing condition, and as previously shown, the improvement was focussed on the end-of-list items (Allan, et al., 2017).

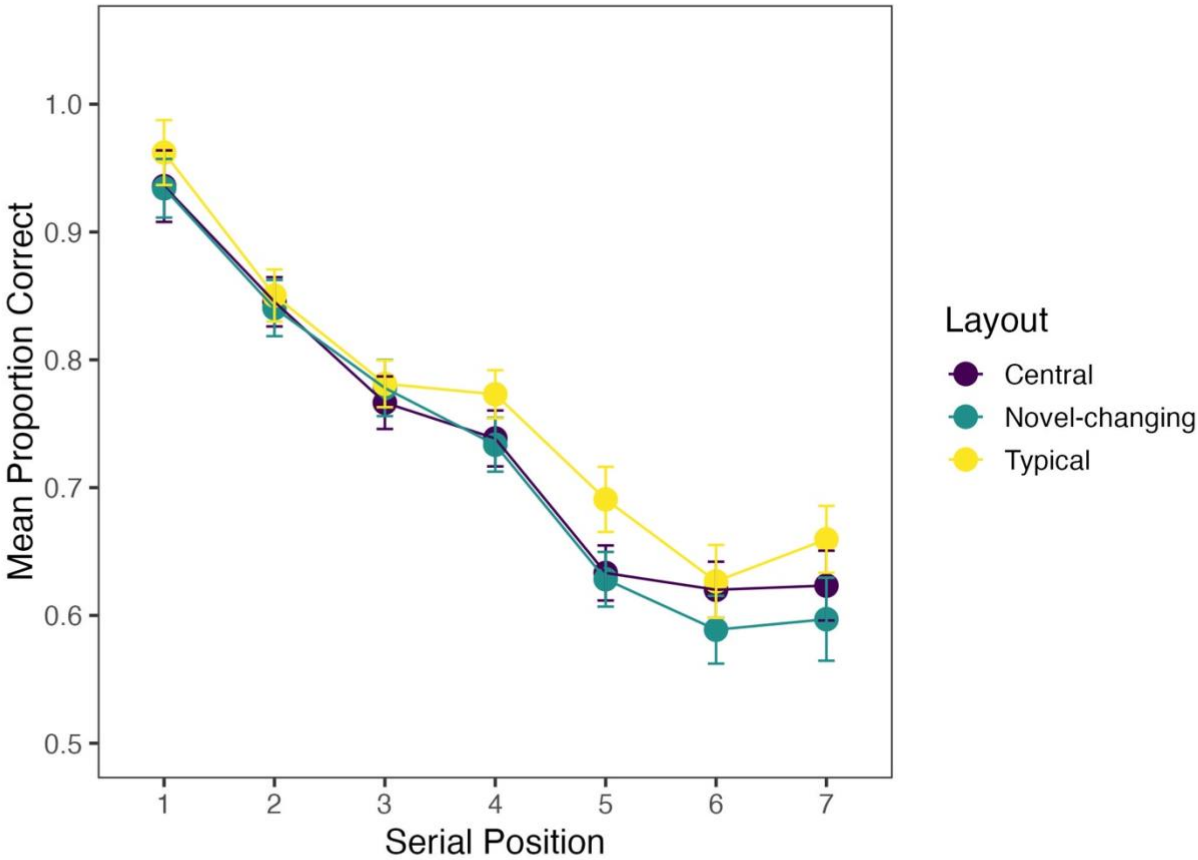

Figure 3.1 Mean proportion correct as a function of condition (central, novel-changing, typical) and serial position (1-7). Error bars mark within-participant standard errors around the mean calculated with the Cousineau-Morey method.

3.2.2.3 How much oculomotor activity occurred during presentation and retention?

Figure 3.2 shows the mean saccade amplitude as a function of layout (central, novel-changing, and typical) for the presentation and retention periods. A factorial Bayesian ANOVA was performed with layout and interest period and found that the best model included the main effects of layout and interest period, and their interaction (*BF* = 3.19 x

10^{416}). This model was preferred over the next best model including only the main effects of layout and interest period by a *BF* of 3.22 x 10^{34}. As there is a clear pattern of higher saccade amplitude in the novel-changing and typical conditions, looking behaviour was further analysed by including only the novel-changing and typical conditions. The best model included a main effect of layout (*BF* = 45014.66), providing evidence for higher saccade amplitude in the novel-changing condition compared to the typical condition. This model was only marginally preferred over including a main effect of interest period by a *BF* of 1.34. The best model was also favoured over the full model including both main effects of layout and interest period, and their interaction (*BF* = 9.89).

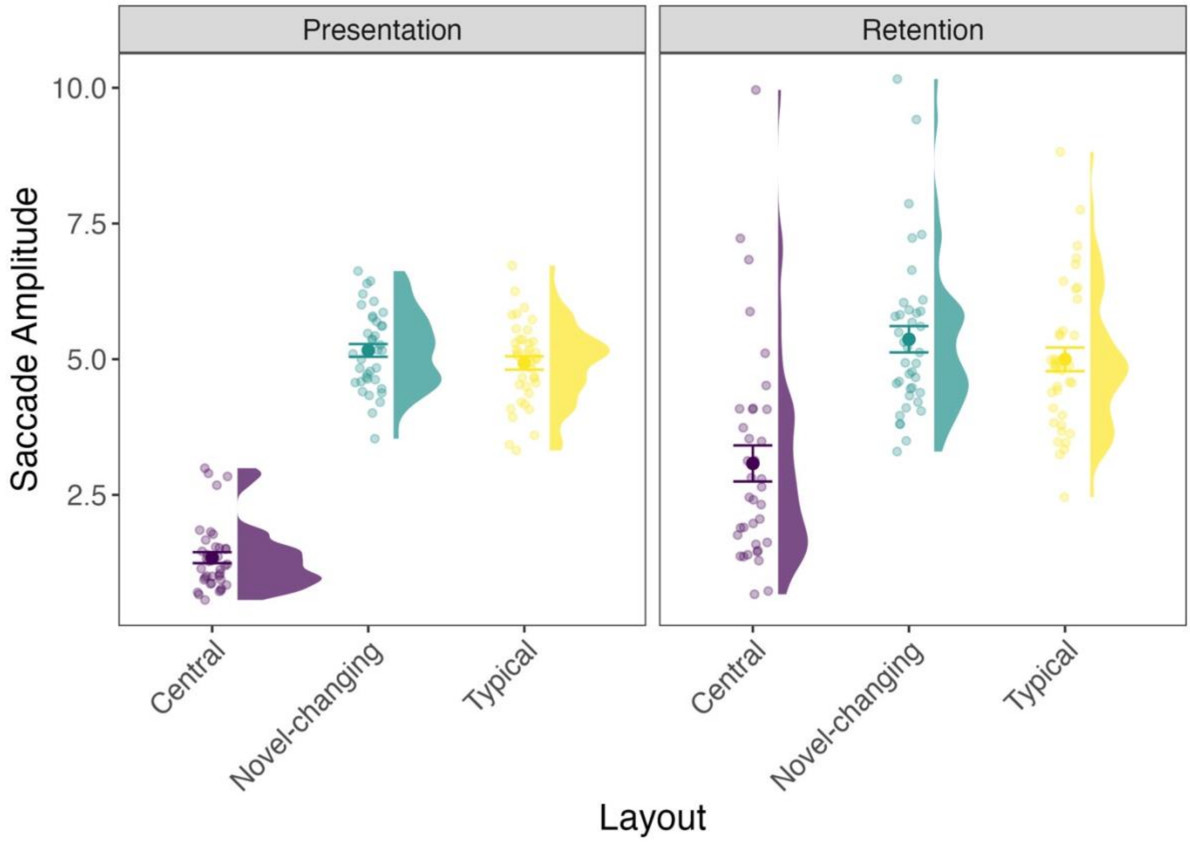

Figure 3.2 Mean Saccade amplitude in visual degrees for each layout condition (central, novel-changing, typical) during the presentation and retention interest periods. Error bars show one standard error around the overall mean per condition. Points represent participant-

specific means. Density curves along the continuous axis reveal data distribution and density across conditions.

3.2.2.4 What was fixated during encoding?

Figure 3.3 shows the average proportion of time participants fixated the incoming item's interest area during its 1200-ms presentation period. Here the denominator was the sum of fixation durations, which exclude time in blink or looking away. It is also important to note that the only relevant interest area for the central condition was the central position. In any further analysis, only the novel-changing and typical layouts are considered as Figure 3.2 shows little looking around in the central condition and the meaning of looking towards one of the blank cells in the central display condition would be unclear. Furthermore, Figure 3.3 shows that the fixation probability pattern is vastly different to the conditions with a spatial array.

To explore the probability of looking at each currently presented item (interest areas were defined to match the size of each cell of the grid) a two-way Bayesian ANOVA was run including layout (novel-changing and typical) and serial position (1-7). The best model was the full model including the main effects of layout and serial position, as well as their interaction ($BF = 1.77 \times 10^{47}$), being decisively favoured over the next best model including only a main effect of serial position ($BF = 6.25 \times 10^{14}$).

To investigate if during the presentation of items participants revisit the locations of previously presented items, a cumulative measure was calculated which considered the sum of proportion of fixations to each of the previously presented items. There was strong evidence that the best model was the full model including the main effect of layout (novel-changing and typical) and serial position (1-7) and their interaction ($BF = 5.54 \times 10^{214}$). The inclusion of the interaction in the model was strongly preferred ($BF = 9.66 \times 10^{16}$). These results suggest that participants look at each of the presented item less often in the typical and novel-changing conditions, whereas in the central condition they mostly remain fixated on the only cell where information appears (Figure 3.3, left panel). However, their looking around appears to be largely targeted as they fixate mostly on the locations of previously presented items during the presentation of subsequent items (Figure 3.3, right panel).

Kendall's correlations were run to investigate the link between this cumulative oculomotor pattern and number of correct responses per participant and per trial. There was no correlation between mean cumulative fixation probability in the novel-changing condition and number of correct responses (τ = .009, p = .95), and no correlation between cumulative fixation probability in the typical condition and number of correct responses (τ = -.045, p = .21). Although participants appear to look back towards the positions of previously presented items in both conditions, the extent of this behaviour does not vary with the extent of recall accuracy.

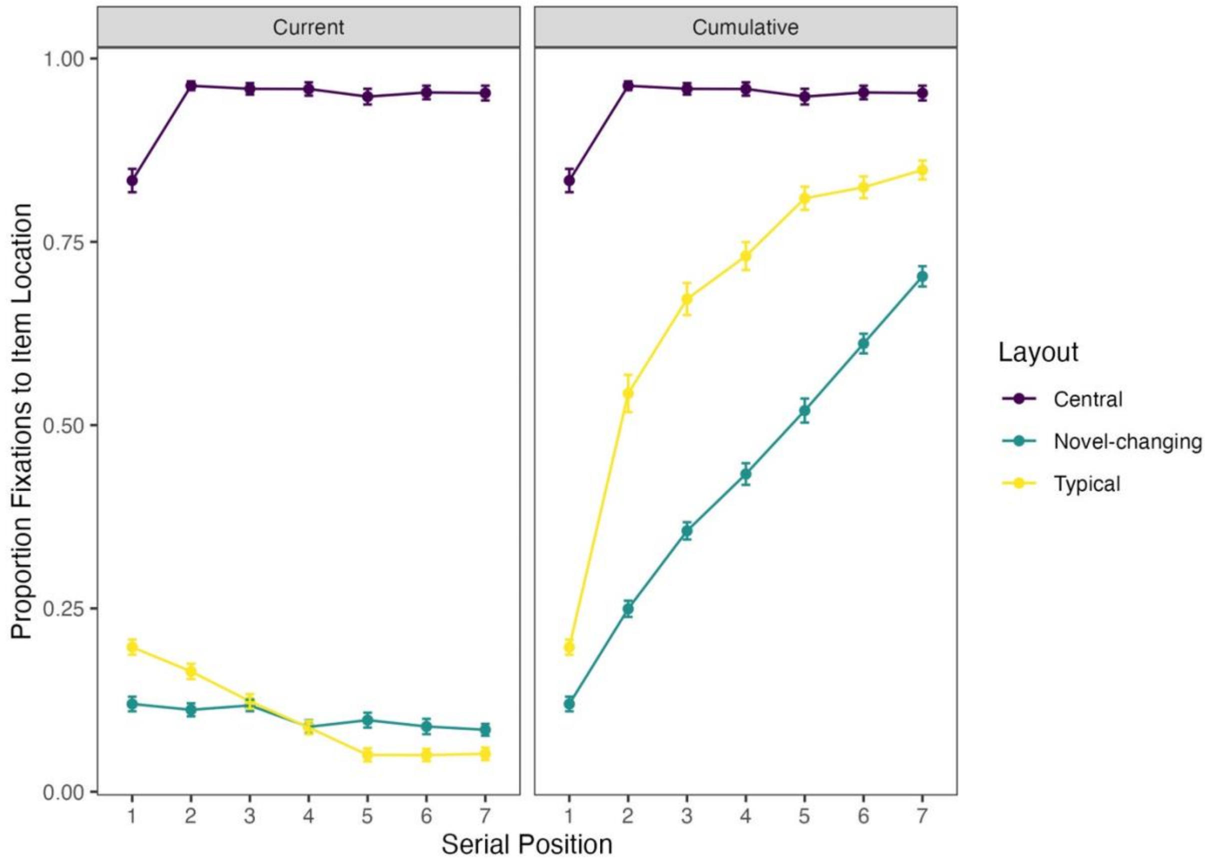

Figure 3.3 Mean proportion of fixations to current (left panel) and cumulative (right panel) item locations as a function of keypad condition (central, novel-changing, typical) and serial position (1-7). Error bars mark within-participant standard errors around the mean calculated with the Cousineau-Morey method. Values for the Central condition are included for comparison only.

3.2.2.5 Did the number of fixated ordered pairs during retention influence accuracy?

The overall saccade amplitude data showed that participants tended to shift their gazes during the 5-second retention period as well as during encoding. Gaze during retention was investigated in further detail to understand whether these gazes supported recall accuracy. Inspired by the analyses of Trembley et al. (2006), trials in which adjacent pairs within the 7-item sequence were fixated in the same order as originally presented, and compared accuracy of trials based on whether 0, 1, or more such ordered fixations were observed during the retention period (see Figure 3.4). If ordered fixations support memory, possibly because they reflect an oculomotor-based spatial rehearsal process, then retention periods that include more instances of ordered fixations should be recalled more accurately.

An ANOVA was run including layout (novel-changing or typical), serial position (1-7), and number of fixated adjacent pairs (0, 1, 2+; more extensive ordered fixations were not so frequently observed to merit additional categories) to investigate if looking towards ordered pairs during retention provided a boost in accuracy (Figure 3.4). The best model included main effects of layout and serial position (BF = 3.68 x 10^{154}), favoured over a model including the main effects of layout, serial position, and adjacent pairs fixated with a BF of 116.93. Including the main effect of serial position was strongly favoured (BF = 4.75 x 10^{152}), and including the layout was preferred with a BF of 183.09. While this shows no evidence that paired looking improved performance, these findings provide further support for an accuracy benefit in the typical compared to novel-changing condition, even without evidence that this benefit is due to paired looking.

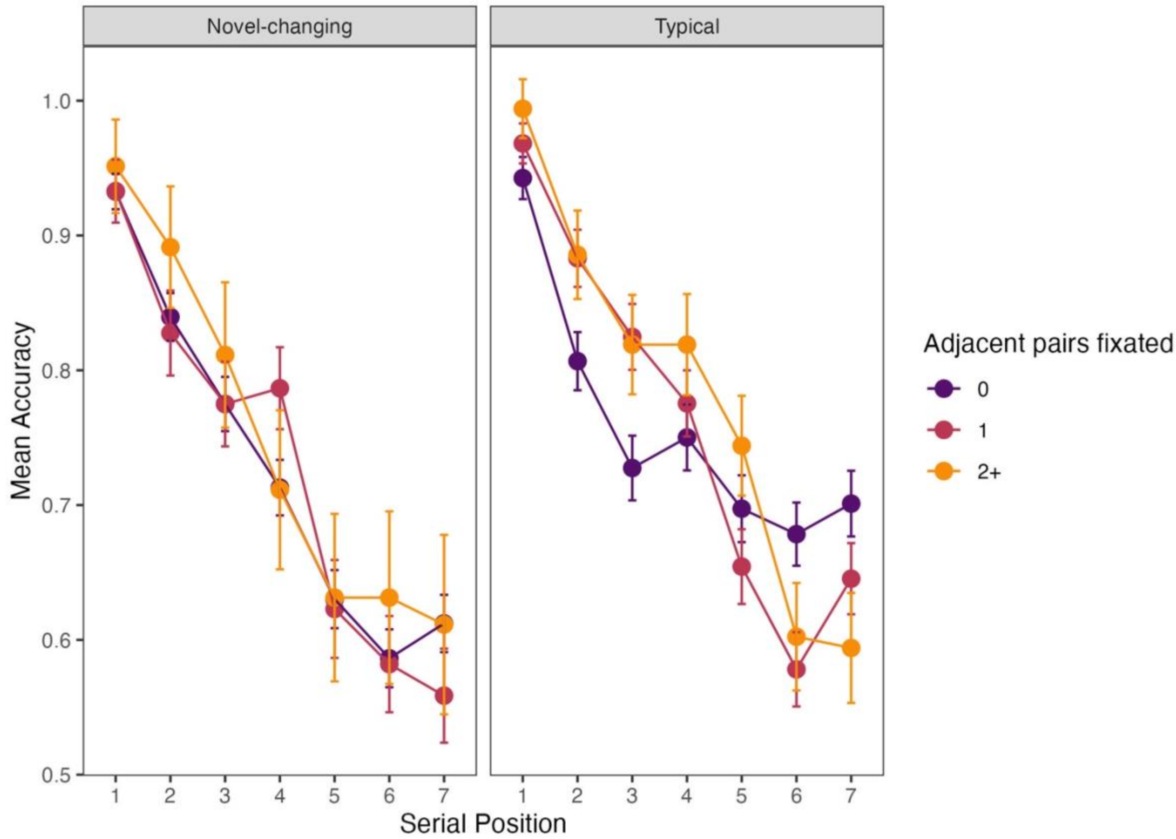

Figure 3.4 Mean accuracy as a function of serial position (1-7) and number of adjacent pairs fixated (0, 1, 2+). Error bars mark within-participant standard errors around the mean calculated with the Cousineau-Morey method.

3.2.2.6 Which pairs were fixated during retention, and did fixating particular pairs influence recall accuracy?

Although looking at more pairs did not reliably predict better overall recall accuracy, perhaps focusing on particular parts of the list benefited recall selectively. The proportion of trials on which each possible ordered pair within the 7-item list was fixated (e.g., proportion on which participants fixated the location of the first-presented item and then the second-presented item, proportion on which they fixated the second and then the third, etc.) were compared, broken down further by display format and whether list recall was correct or not (Figure 3.5).The best model included the main effects of layout and serial position (*BF* = 3212.15), which was preferred over the next best model including only the main effect of layout with a

BF of 2.83. Excluding the interaction between layout and serial position was favoured (*BF* = 13.81). Including the effect of layout was strongly favoured, suggesting that more paired looking occurred in the typical keypad condition (*BF* = 1415.13). In the novel-changing layout, participants were less likely to fixate ordered pairs overall, with no obvious preference for fixating pairs from particular positions in the list. In the typical keypad condition, fixating pairs was more likely, particularly for early- and late-list pairs. More ordered looking did not lead to better overall recall accuracy (*BF* = 9.02).

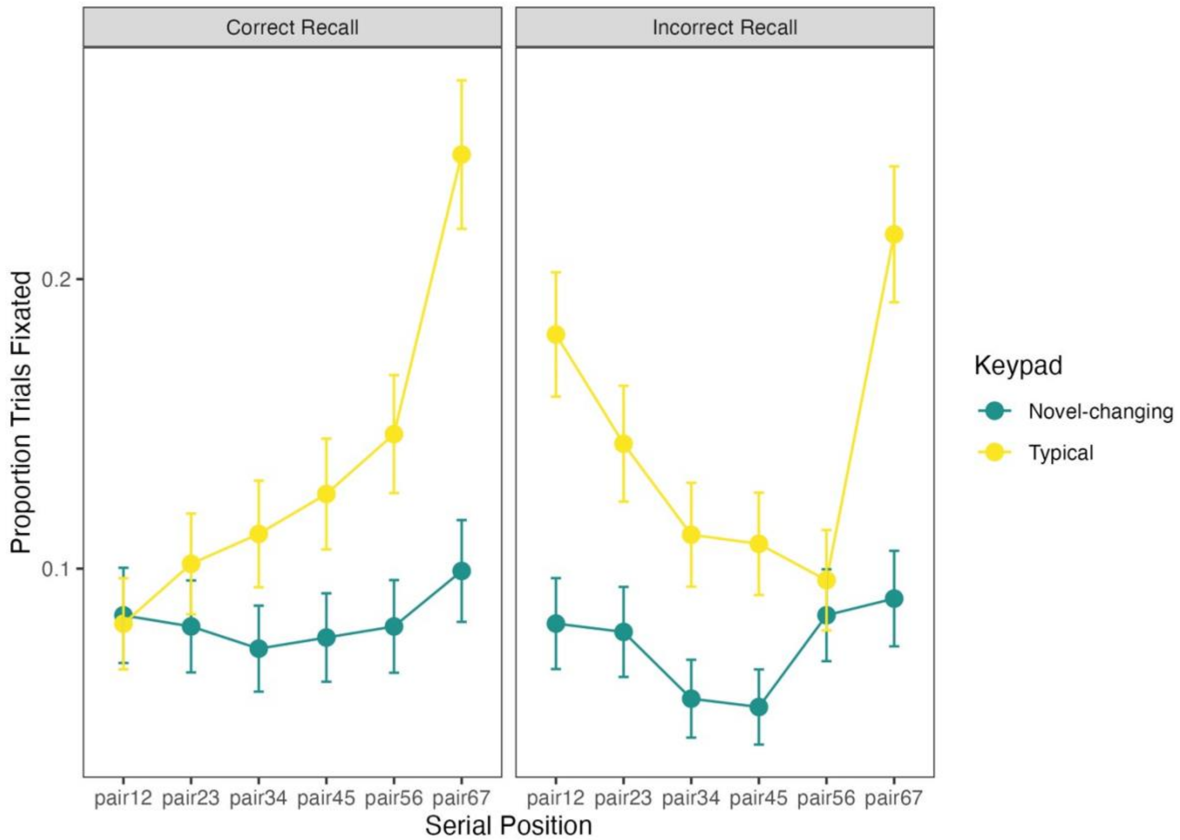

Figure 3.5 Mean proportion of trials as a function of fixated pairs and keypad condition during the retention interval. Error bars mark within-participant standard errors around the mean calculated with the Cousineau-Morey method.

3.2.2.7 Were serial position items revisited during the retention interval?

Given previous findings that show stronger visuospatial boot-strapping benefits with immediate recall, it could be the case that gaze-based support for maintenance is rather short-lived, and therefore may be concentrated early during the retention interval. To investigate the time course of where oculomotor activity is directed throughout the retention interval, the probability of fixating each of the relevant digits was considered continuously across the 5-second retention period. The fixation probability measure was based on all samples in fixations and saccades and was calculated against all samples in each interest area in 20ms-bins.

After a visual inspection of Figure 3.6 the analysis was focused on the first 1000ms of the retention interval. An ANOVA was performed with layout and interest areas corresponding to the seven serial positions during encoding as factors. The best model was the full model including the main effects of layout, interest area, and their interaction (BF = 2.98×10^{35}). The best model was strongly favoured over the next best model which included the main effect of interest area by a BF of 6.23×10^{12}. Including the interaction was favoured by a BF of 7.35×10^{13}.The best model was also preferred over a model including only the main effect of layout by 3.64×10^{36}. To further investigate if looks to the last presented digit are driving the VSB effect, the fixation probability of the last digit was excluded from the analysis and a 2 (novel-changing and typical) by 6 (interest areas of serial positions 1-6) Bayesian ANOVA was run across the first 1000ms of the retention period. The best model for this data included only the main effect of layout, but there was weak evidence for favouring it over the null (which included only between-subject variance) with a BF = 0.40. Taken together these findings suggests that main difference between the novel-changing and typical keypad layouts is coming from an increase in the looks to the last presented digit in the typical keypad condition.

Kendall's correlations was also run to investigate the link between this pattern of looking at the last digit during the first 1000ms of the retention period and number of correct responses. There was no correlation between fixation probability in the novel-changing condition and mean number of correct responses (τ = -.06, p = .42), and also no correlation between fixation probability in the typical condition and mean number of correct responses (τ = -.00005, p = .81). There was also no correlation found between accuracy for the last item and the probability of fixating the same item during the first 1000ms of the retention period in the novel-changing condition (τ = .004, p =.86), and in the typical condition (τ = .023, p =.54).

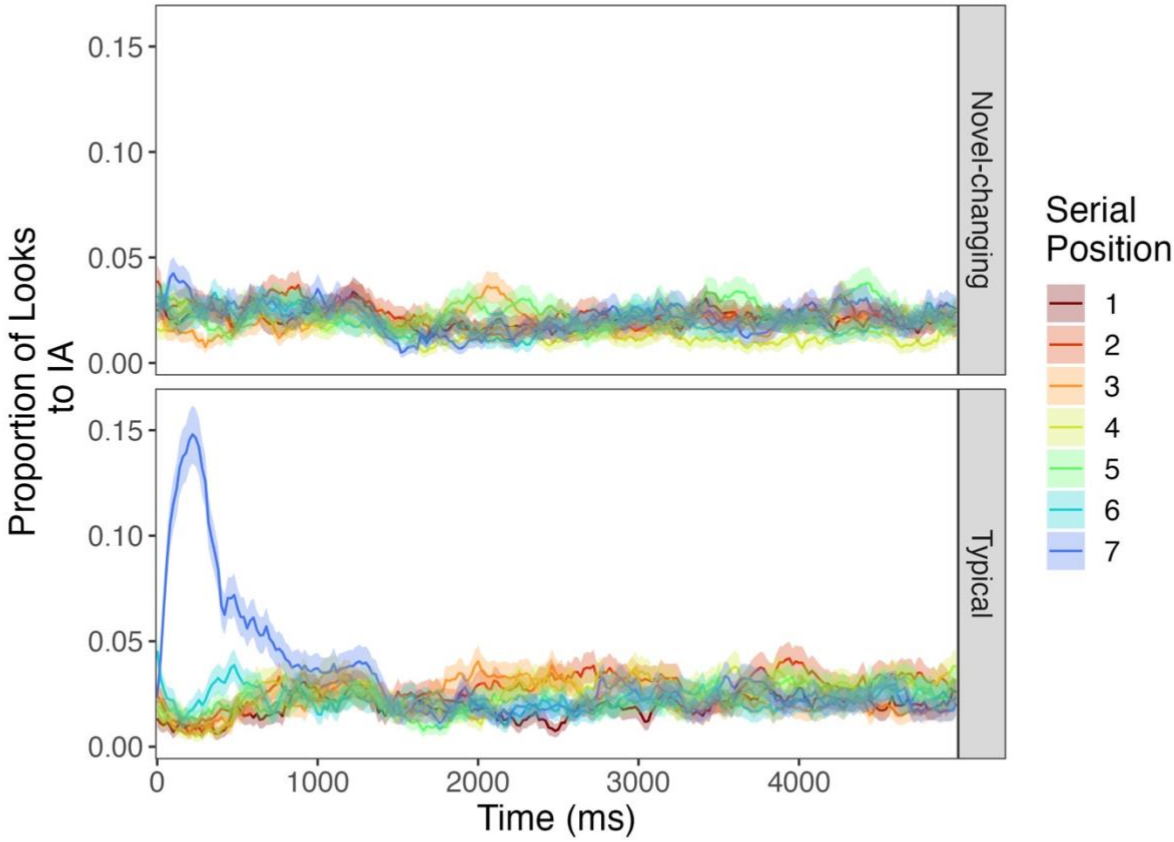

Figure 3.6 Time course of the proportion of looks to each digit interest area as a function of layout (novel-changing and typical). Shaded areas represent within-participant standard errors around the mean calculated with the Cousineau-Morey method.

3.2.3 Discussion

Experiment 1 aimed to explore gaze when encoding and maintaining a list of seven digits in a visuospatial bootstrapping task and found that the familiar keypad layout was associated with a unique gaze pattern. When encoding digits in the familiar keypad layout, participants were more likely to look back towards previously presented locations than when digits were arranged in a novel layout. They were also more likely to fixate ordered pairs of digit locations during retention when digits had been presented in the familiar layout, particularly towards the end of the list. However, neither of these tendencies directly predicted list recall accuracy, nor recall of the end-of-list items. These findings confirm that participants approach the familiar layout lists differently than the random or centrally presented lists and suggests that oculomotor activity may subtly distinguish these conditions. However, no direct evidence was observed that gaze patterns themselves reinforce accurate memory.

The finding that in both the novel-changing and typical condition fixation probability of incoming items is low compared to the central condition is consistent with previous research which found patterns consistent with saccadic suppression during spatial compared to verbal memory encoding (Czoschke et al., 2019; Lange & Engbert, 2013; Patt et al., 2014). Taken together with findings from the current study that lower saccade amplitude was found in the central condition compared to the conditions with a spatial array, this suggests that participants looked at the incoming items precisely in the central condition without much looking around. In the novel-changing and typical keypad conditions there was more oculomotor activity, and while the probability of fixating each incoming item was low, part of the reason for that were targeted looks back to previously presented items, shown by the cumulative increase in the proportion of fixations landing on relevant positions as the list progressed, which was especially pronounced in the typical keypad condition. This suggests that there is a unique oculomotor behaviour when a spatial array is present, allowing the revisiting of locations associated with prior list items. In a task asking participants to either recall five bigrams, their unique locations, or the combination of both the bigrams and their locations, Czoschke et al. (2019) observed a pattern of lower fixation probability in the location recall condition compared to the verbal and combined conditions. However, they observed the opposite pattern when they considered looking back to previous items during the encoding phase, with lower regression probability in the verbal recall compared to the spatial and combined recall conditions. Even though the task used in this experiment was primarily verbal, the observed gaze patterns in the grid presentation conditions, especially where the mapping between digit and location was familiar, were consistent with those found by Czoschke et al. (2019) for spatial memory tasks. The correspondence between gaze patterns in the current study in displays where visuospatial bootstrapping was possible and Czoschke et al.'s spatial recall conditions suggests that presenting verbal information in unique locations of a spatial array afforded participants opportunities to look back to previous items, which was most prevalent when the layout was already known. Therefore the gaze patterns observed during visuospatial bootstrapping were consistent with those observed during spatial encoding, which is in keeping with the hypothesis that a partial spatial trace is "bootstrapped" onto to an otherwise verbal task, which may then boost recall. However, no direct evidence was found that this pattern was associated with a memory cost or benefit.

Investigating the retention period, a higher proportion of trials where pairs of digits were fixated was found in the typical compared to novel-changing condition, with the biggest difference observed for the last presented pair. But again, no direct memory benefit associated with this pattern was observed. Further, at the beginning of the retention interval a stronger gaze bias was found towards the last-presented item in the typical compared to the novel-changing condition. While it is possible that this only reflects lingering at the location of the last presented digit, the absence of the same bias in the novel-changing layout suggests that there is more to it than that: possibly, these gazes could reflect attempts to reinforce memory for end of list items, which might sometimes result in better performance. Though no direct evidence for that claim was observed, it should be noted that the observed visuospatial bootstrapping effect in this study was rather small (d = 0.14) compared to other investigations (e.g. Allen et al., 2023; $d = 0.30$). Though a statistically significant difference was observed between the familiar and novel layouts consistent with many previous studies, this difference did not emerge in analyses including the intermediate centrally presented condition. This could reflect that the observed boost in the familiar condition compared to central and likewise the cost from central to novel were rather modest and focused towards the end of list (though this also replicates previous findings; Allan et al., 2017). The overall low probability of revisiting previously presented item locations during the retention period is consistent with previous findings of low oculomotor activity during the retention period (e.g., Pearson & Sahraie, 2003, Experiment 5; Morey et al., 2018). However, the bias towards the last-presented item in the familiar layout condition lends support to Tremblay et al.'s (2006) argument that eye movements may play a role in rehearsing visuo-spatial information and to previous research suggesting participants may intentionally revisit locations associated with memorized items (e.g., Altmann, 2004; Richardson & Spivey, 2000; Ferreira et al., 2008; van Ede et al., 2019). Although previous research has associated this bias with verbal and visuospatial performance benefits (Hollingworth, 2009; Laeng et al., 2014; Laeng & Teodorescu, 2002; Scholz et al., 2016), the current study did not provide clear evidence supporting such advantages.

3.3 Experiment 2

In Experiment 2, the VSB paradigm was modified to incentivise eye movements and allow clearer interpretation of gaze data. Retro cues were incorporated to reduce the number of items to be recalled and to select one item at a time from a memorised list, which allows for a more refined investigation of gaze activity by providing one location to be identified as the area of interest. The use of retro cues is informed by substantial evidence indicating their effectiveness in directing both overt and covert attention internally. Retro cues, as reviewed by Souza & Oberauer, (2016), operate analogously to the cues in the Posner paradigm (Posner, 1980), which direct attention to the anticipated location of a relevant stimulus. However, unlike in the Posner paradigm where cues precede stimulus presentation, retro cues are introduced after the encoding of stimuli into memory, with the purpose of orienting attention towards specific representations within working memory. This attentional guidance is suggested to enhance the storage and accessibility of the targeted item, thereby facilitating improved recall performance compared to conditions where attention is distributed equally across all items (Griffin & Nobre, 2003; Lepsien et al., 2005; Sligte et al., 2008).

The strategic spacing of stimuli across the visual field plays a crucial role in influencing participants' eye movement behaviours and, consequently, the quality and interpretability of the collected data. Spacing out stimuli, as opposed to clustering them closely together, serves several key purposes that enhance the study's methodological robustness and the validity of its findings. Firstly, spacing stimuli more broadly across the visual field encourages a wider range of eye movements, including both saccades and fixations. This increased movement is essential for capturing a comprehensive dataset that reflects natural viewing patterns and the dynamics of visual attention. Wider spacing also helps to minimize potential confounds related to crowding and visual interference. When stimuli are placed too close together, there is a higher risk that adjacent stimuli might influence the participant's attentional focus, either by drawing attention away from the target stimulus or by creating ambiguity about which stimulus is being fixated upon. Such crowding can confound data interpretation, making it challenging to determine the specific attributes of a stimulus that are driving attentional engagement. By spacing stimuli apart, each stimulus was allowed to be processed more independently, enabling cleaner, more interpretable eye movement data.

In Experiment 2 a static rather than a dynamic novel keypad layout was used with a spatial arrangement of digits that is different to the typical keypad condition, and which remains unchanged over trials as in the typical keypad condition. This constant layout enables participants to gradually develop and refine a cognitive map. Comparing a static novel layout to a typical keypad layout allows us to investigate if eye movement patterns associated with the visuospatial bootstrapping effect can be observed only when long-term memory representations are utilised.

Backward recall was included in the current working memory task within the context of investigating the visuospatial bootstrapping (VSB) effect, which offers a novel avenue to deepen our understanding of the mechanisms underpinning working memory processes. Research indicates that anticipation of forward recall leads participants to preferentially employ phonological encoding strategies, leveraging auditory and verbal information (Guitard et al., 2020; Miles et al., 1991; Watkins et al., 2000). In contrast, when participants anticipate backward recall, there is a shift towards more pronounced reliance on visuospatial encoding strategies. This shift is crucial for understanding the dynamics of working memory, as visuospatial representations play a significant role in backward recall tasks (Donolato et al., 2017). Such a differential reliance on encoding strategies underscores the need to investigate backward recall to capture a more comprehensive picture of cognitive processes involved in working memory. Previous research has predominantly concentrated on forward recall, leaving a gap in our knowledge regarding how backward recall might interact with the VSB effect. The rationale for exploring backward recall stems from the hypothesis that the direction of recall (forward vs. backward) may differentially engage cognitive encoding strategies and memory representations. Incorporating backward recall into the study design allows for a more nuanced exploration of the cognitive mechanisms that facilitate the integration of visuospatial and verbal information in working memory. It enables an investigation into whether the VSB effect can enhance recall performance in backward recall tasks by bolstering visuospatial encoding and retrieval strategies. Such an investigation not only fills a gap in the existing literature but also contributes to a more detailed understanding of the interplay between visuospatial and phonological components of working memory.

3.3.1 Method

3.3.1.1 Participants

Forty-one participants took part in the experiment. Eight participants were excluded due to poor eye tracking calibration and validation values (the mean spatial accuracy was worse than 0.5 degree or a maximum spatial accuracy worse than 1 degree for each performed validation procedure). The 33 remaining participants (12 male) ranged from 19 to 40 (M= 24.47; SD= 4.9). All participants were students at Cardiff University and were recruited via the School of Psychology's participant panel, social media and word of mouth. All had normal or corrected-to-normal vision.

3.3.1.2 Design, materials, and procedure

The task was administered using Experiment Builder (SR Research) on a display monitor with a resolution of 1920 x 1080 pixels (width 53.2 cm; height: 30 cm; refresh rate 60Hz), viewed at a distance of 60 cm. Eye movements were recorded using a desk-mounted SR Research EyeLink 1000 Plus eye tracker which recorded monocular eye movements at 1000Hz using pupil and corneal reflection tracking. Fixations were detected using the standard SR Research algorithm.

Participants were tested individually in a dimly illuminated room. A 5-point calibration grid, followed by a 5-point validation grid was used to fit and test the spatial accuracy of the eye-tracker at the start of each block. If validation showed a mean spatial accuracy worse than 1 visual degree or a maximum spatial accuracy worse than 2 visual degrees, calibration and setup were repeated. Each trial began with a drift check (a central point which the participant had to fixate) that was manually accepted by the researcher, and if both eyes had an error of more than 0.5 degree, then the calibration and validation procedure was repeated. Participants completed 6 practice trials and 6 randomly ordered blocks of 12 trials each, one for each combination of the layout (central, typical, novel-static) and recall order (forward, backward) conditions (72 experimental trials in total). Both the presentation of blocks and trials within blocks was randomised.

To-be-remembered 7-digit lists were generated from the set {0, 1, 2, 3, 4, 5, 6, 7, 8, 9} without replacement. Each digit was presented in black font Arial with a size 60 against a medium grey background (#999999). In the central condition, a single digit was presented in the middle of the screen. In the typical layout condition, digits were arranged as they would be found on a telephone keypad, with the middle point between the location of digit 5 and 8 being the central point (see Table 1 in Appendix for a full list of coordinates for each digit). In the novel static display, the digits were arranged at the same locations in different order (8, 1, 7, 6, 9, 3, 2, 5, 0, 4 instead of 1, 2, 3, 4, 5, 6, 7, 8, 9, 0). As in Experiment 1, the central display condition had no contextual meaning, and eye movement analyses that aim to determine whether looking benefited accuracy contrasted the typical keypad and novel-static displays only. In descriptive accuracy analyses, data was included from the central display condition to demonstrate the anticipated performance improvements with standard keypad layouts and the expected drawbacks when using novel-static displays compared to the central display. Additionally, an initial examination of saccade amplitude was performed across all three layout conditions, confirming that participants exhibit significantly reduced eye movement in the central display condition.

Each trial in the central condition began with a blank display presented for 250ms, and each trial in the typical and novel-static conditions began with presenting digits in a keypad layout for 250ms in a 3 x 3 +1 matrix (see Figure 3.7). The to-be-remembered sequence was then presented. Seven digits were presented visually one by one, each for 1000ms followed by a blank inter-item interval of 250ms after each digit which contained a blank display in the central condition or a keypad layout in the typical and novel-static conditions. The digits were presented in black font Arial with a size 60. In the central condition, each digit was presented in the middle of the screen, while in the typical and novel-static keypad displays, all digits (0-9) were presented in a keypad layout and the relevant digit was highlighted by presenting a 200 by 200 pixel light grey (#C0C0C0) square behind the relevant digit. After the final digit, a 1000ms blank retention display was presented.

This was followed by three central cues (e.g. 1^{st},2^{nd}) that refer to the sequential order of the previously presented digits, visible for 500ms and each followed by a 2000ms blank screen. The sequential position of these cues was either in a forward fashion (e.g. 1^{st}, 4^{th}, 6^{th}; the first cue was either 1^{st}, 2^{nd}, or 3^{rd}, the second cue was 3^{rd}, 4^{th}, or 5^{th}, and the third cue was either 5^{th} or 6^{th}, or 7^{th}) or in a backwards fashion (e.g. 7^{th}, 3^{rd}, 2^{nd}; ; the first cue was either 5^{th} or 6^{th}, or 7^{th}, the second cue was 3^{rd}, 4^{th}, or 5^{th}, and the third cue was 1^{st}, 2^{nd}, or 3^{rd}). After each of the blank screens, participants were then presented with the recall screen containing all of the digits (0-9) horizontally (see Figure 3.7d), prompting participants to click on the digit that was presented in the relevant serial position as indicated by the cue. To keep the timings consistent, the mouse click response was timed and always took 3000ms, with the next retro-cue sequence beginning if the participant did not make a response within the 3000ms, or if the participant made a response before this, a blank screen was presented until 3000ms had elapsed since the presentation of the recall screen. Upon a mouse click on a valid digit location (or timing out) after the third and final retro-cue sequence, the next trial began.

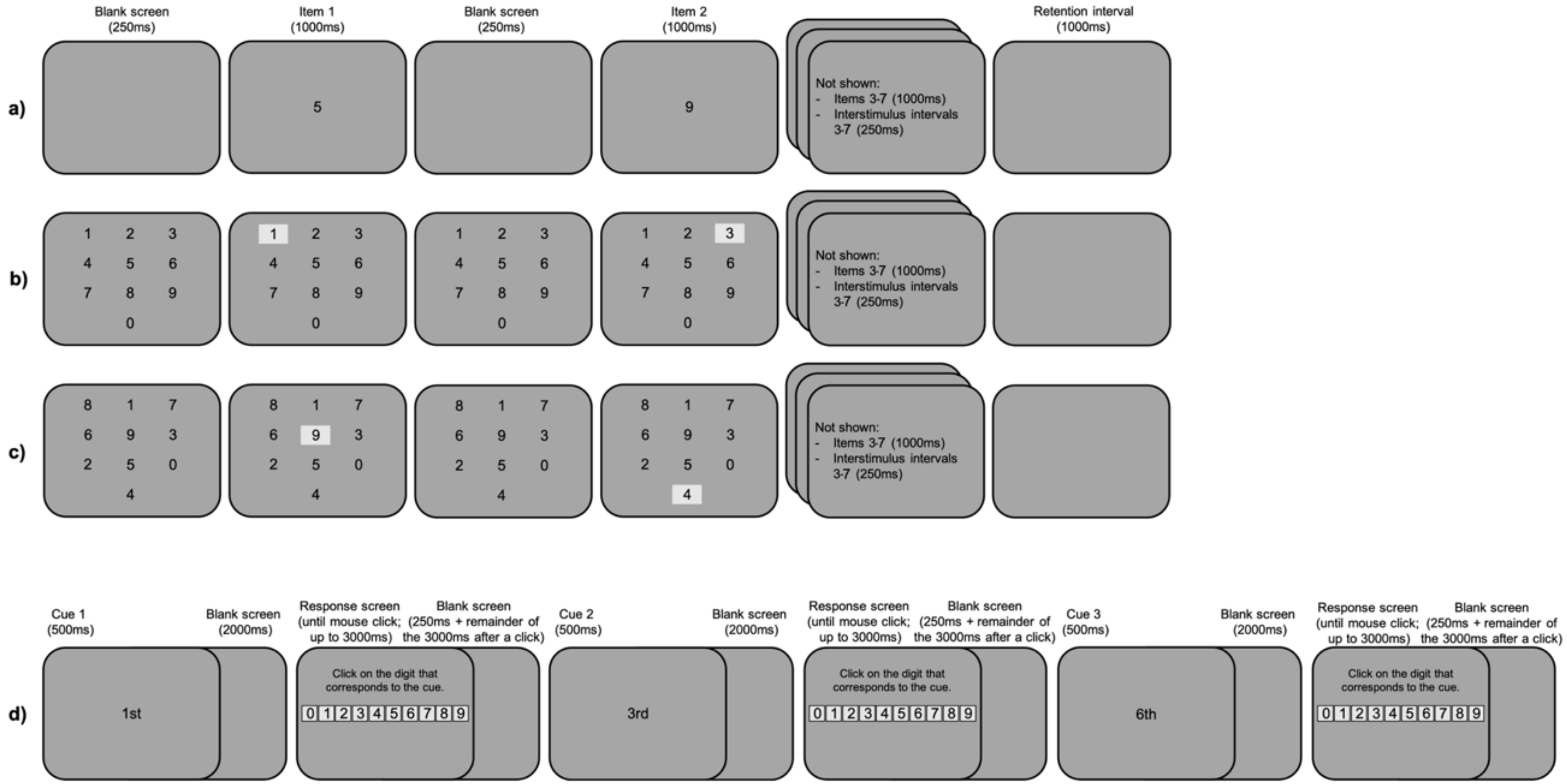

Figure 3.7 Trial sequence for Experiment 2 during each of the conditions: a) central b) typical keypad, c) novel static; d) illustrates the retro cue and response period sequence.

3.3.2 Results

3.3.2.1 Data Analysis

The same data analysis plan as in Experiment 1 was used, with the exception of the size of the interest areas: in Experiment 2, interest areas were defined as rectangles with size 360 x 270 pixels located at the centre of each digit.

3.3.2.2 Recall Accuracy

Figure 3.8 shows the recall accuracy as a function of layout (central, novel-changing keypad, and typical keypad), recall order (forward or backward) and response position (based on cues 1, 2 and 3). A three-way Bayesian ANOVA including layout, order, and response position revealed that the best model was the full model (BF = 1.98×10^{17}). To explore accuracy for each condition, the forward and backward recall order were considered separately. A two-way Bayesian ANOVA was run including layout and response position to investigate accuracy when recalling in forward order. The best model was the full model including the main effects of layout and response position, and their interaction (*BF* = 1.93×10^{13}). This was strongly preferred over the next best model which included only a main effect of cue (*BF* = 1007.49). There was strong evidence for including the interaction in the full model (*BF* =19532.48). To contrast accuracy when recalling in backward order a two-way Bayesian ANOVA was run including layout and response position as predictor variables. The best model included the main effects of layout and response position (*BF* = 89.18). Excluding the interaction in the full model was favoured with a *BF* of 2.70. Including the main effect of layout in the best model was favoured by a *BF* of 4.93, and including the main effect of response position in the best model was favoured by a *BF* of 23.36.

To further investigate the keypad conditions, only the novel-static and typical layouts were considered. The best model for forward recall order included only a main effect of response position (BF = 1.64 x 10^{12}). This was preferred over the next best model including both the main effects of layout and response position by a *BF* of 5.58. Excluding the main effect of layout and the interaction between response position and layout from the best model was favoured with a *BF* of 52.98. The best model for backward recall order was the full model, including the main effects of layout and response position, as well as their interaction (*BF* = 14.45). Including the interaction effect was favoured with a *BF* of 1.64. These findings indicate that while in forward recall there was no effect of layout, performance was higher in backward recall condition for typical compared to novel-static layout.

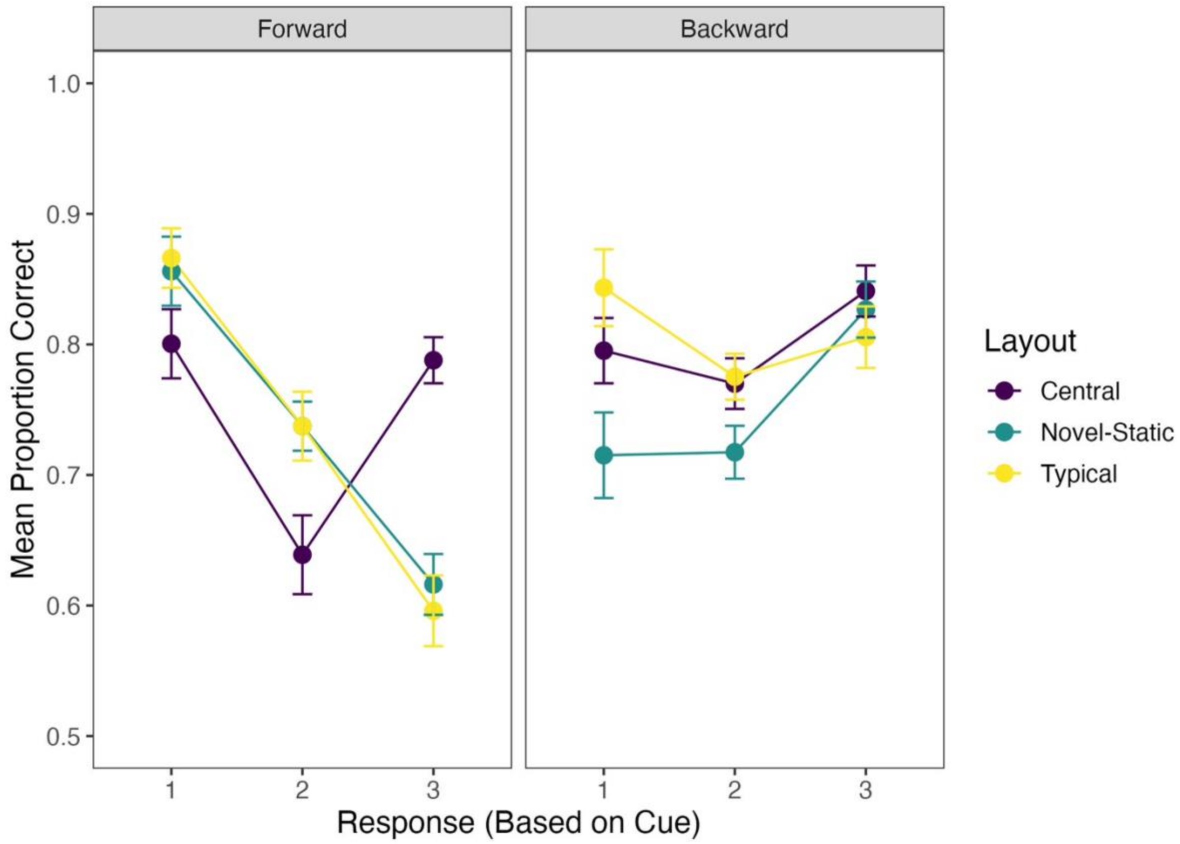

Figure 3.8 Mean proportion correct as a function of layout (central, novel-static, typical), recall order (forward, backward), and response position (1, 2 or 3). Error bars mark within-participant standard errors around the mean calculated with the Cousineau-Morey.

3.3.2.3 How much oculomotor activity occurred during presentation and retention?

Saccade amplitude during the presentation and retention periods is illustrated in Figure 3.9. The encoding period was investigated first by running a two-way Bayesian ANOVA with layout (central, typical, novel-static) and recall order (forward, backward) as predictors. The best model included the main effects of layout and order ($BF = 1.63 \times 10^{132}$), which was favoured over the next best model which included both the main effects and their interaction ($BF = 3.08$). The inclusion of the main effect of order in the best model was favoured with a BF of 58.07, while the inclusion of the main effect of layout in the best model was strongly favoured ($BF = 9.06 \times 10^{132}$). These findings indicate that participants had to move their eyes around during encoding in both spatially arrayed conditions.

To investigate the difference between the typical and novel-static conditions, the central conditions were excluded. The best model was the full model including the main effects layout and order, as well as their interaction ($BF = 8179.18$). However, there was no clear evidence of the best model being preferred over a model containing only the main effect of order ($BF = 1.69$), revealing that the saccade amplitude during encoding in the forward order is higher compared to the backward order.

Saccade amplitude was then analysed during the retention period. The best model included only the main effect of layout ($BF = 4.59 \times 10^{50}$). The best model was favoured over the full model with a BF of 61.92. Following this up by excluding the central conditions, no evidence was found for significant differences between the conditions, with the best model including the main effect of layout barely preferred over the null model including only between-subject variance (BF = 3.10).

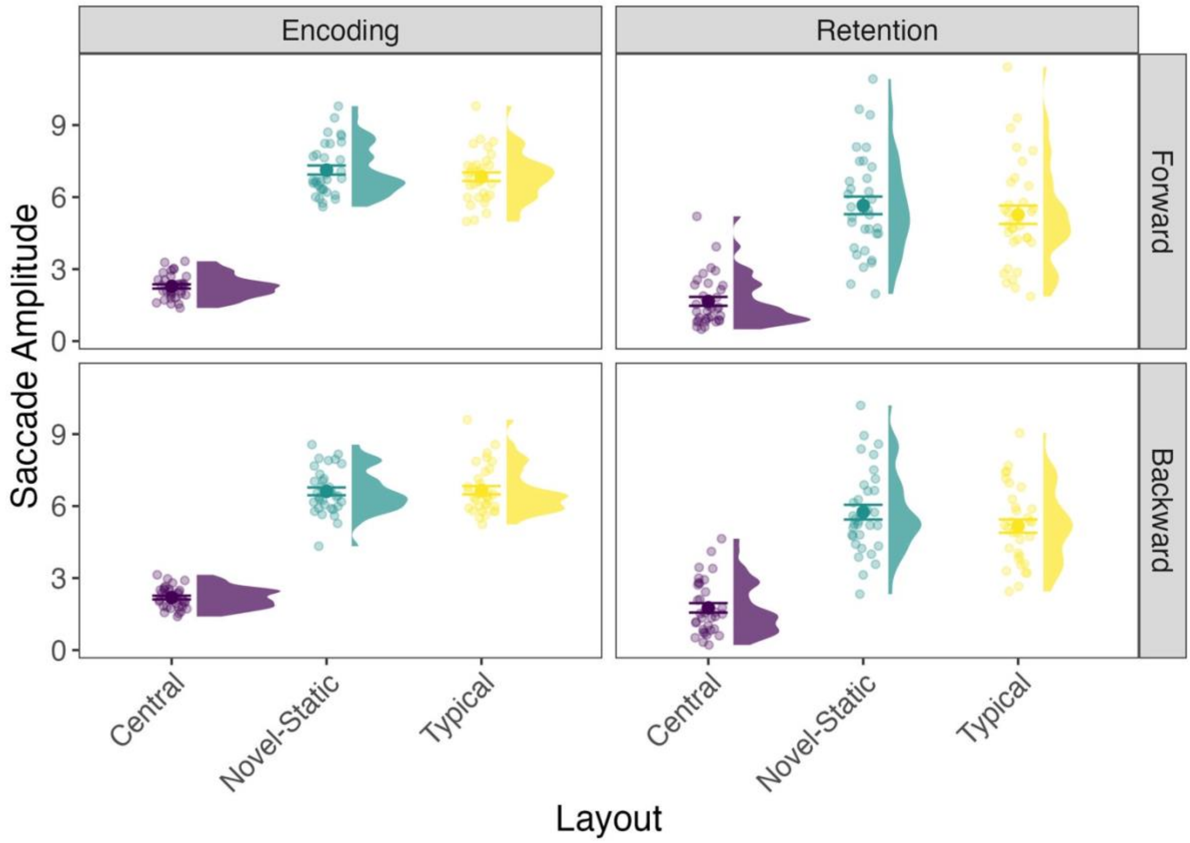

Figure 3.9 Mean saccade amplitude in visual degrees for each layout condition (central, novel-static, typical), recall order (forward, backward) during the presentation period and retention period (preceding the period with retro cues). Error bars show one standard error around the overall mean per condition. Points represent participant-specific means. Density curves along the continuous axis reveal data distribution and density across conditions.

3.3.2.4 What was looked at during encoding?

Figure 3.10 shows the average proportion of time participants fixated the incoming item's interest area during its 1250-ms presentation period. The only relevant interest area for the central condition was the central position. In any further analysis the novel-changing and typical layouts were considered as Figure 3.9 shows little looking around in the central condition. Furthermore, Figure 3.10 shows that the fixation probability pattern with central presentation is vastly different to the conditions with a spatial array.

To explore the probability of looking at each currently presented item a two-way Bayesian ANOVA was run including layout (novel-static and typical) and serial position (1-7) in the forward condition. The best model was the full model including the main effects of layout and serial position, as well as their interaction ($BF = 5.41 \times 10^{38}$), being decisively favoured over the next best model including only a main effect of serial position ($BF = 1.80 \times 10^{3}$). The best model for backward order was the full model ($BF = 2.77 \times 10^{31}$), with strong evidence for a preference for this model over the next best model including only a main effect of serial position ($BF = 9.21 \times 10^{3}$).

To further investigate the looking behaviour during the presentation of items, a cumulative measure was calculated which considered the sum of proportion of fixations to each of the previously presented items. For forward order, the best model was the full model including the two main effects (layout and serial position) and their interaction ($BF = 2.31 \times 10^{296}$). This model was favoured over the next best model containing the main effects of layout and serial position ($BF = 1.19 \times 10^{3}$).

Kendall’s correlations were run to investigate the link between this cumulative oculomotor pattern and number of correct responses. There was no correlation between mean cumulative fixation probability in the novel-static layout in forward order and trial accuracy ($\tau = -.04$, $p = .67$), and no correlation between cumulative fixation probability in the novel-static layout in backward order and trial accuracy ($\tau = -.011$, $p = .12$). There was a weak negative correlation between mean cumulative fixation probability in the typical layout in forward order and trial accuracy ($\tau = -.14$, $p = .01$), and also between mean cumulative fixation probability in the typical layout in backward order and trial accuracy ($\tau = -.13$, $p = .03$).

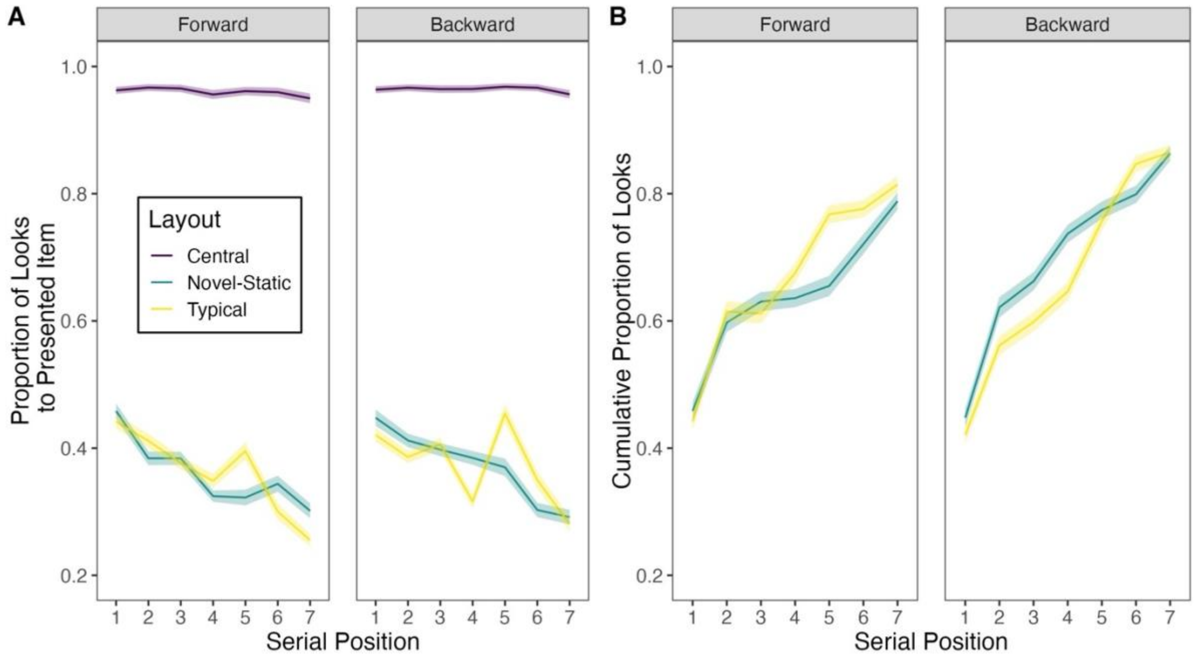

Figure 3.10 Mean proportion of fixations to incoming items (A) and cumulative item locations (B) as a function of keypad condition (central, novel-changing, typical) and serial position (1-7). Error bars mark within-participant standard errors around the mean calculated with the Cousineau-Morey method.

3.3.2.5 Were serial position items revisited during the retention interval?

To investigate the proportion of looks during the 1000ms retention interval (illustrated in Figure 3.11) to the interest area of each of the presented items the fixation probability was averaged across the retention period and a model was run with layout (typical, novel-static), order (forward, backward) and serial position (1 to 7). The best model was the full model which included the main effects of layout, order, serial position, and their interactions (BF = 1.07 x 10^{57}).

After visually inspecting Figure 3.11, the probability of fixating the 5th and 7th item was investigated separately as most of the difference between conditions seems to stem from these and also they are of the greatest relevance for the current investigation because the looks to the 5th item, which was the first possible item from the chunk to be probed (5th,6th ,

7^{th}) and the 7^{th} item, which is the last presented item, would indicate different maintenance strategies.

To further investigate these patterns, only the probability of fixating the last 7^{th} item was considered. A model was run with layout (typical, novel-static) and order (forward, backward) and found that the best model included the main effect of order (*BF* = 1.54). The best model was preferred over the next best model which included only the main effects of layout and order with a *BF* of 1.72.

The average fixation probability to serial position 5 was then considered during the retention period by running a Bayesian ANOVA with layout and order as predictors. The best model contained the main effects of layout and order (*BF* = 6.12 x 10^{11}), with weak evidence for a preference over the next best model which included the main effects and their interaction with a *BF* of 2.23. There was moderate evidence for higher probability of fixating the interest area of the 5^{th} presented item in the typical backward condition compared to the typical forward condition (*BF* = 4.36). The probability of looking at the 5^{th} presented item was also higher in the novel backward condition compared to the novel forward condition (*BF* = 3.91 x 10^3). When considering only the forward conditions, a higher fixation probability was found to the 5^{th} item in the typical layout compared to the novel layout (*BF* = 9.01 x 10^4). The typical backward layout also had a higher fixation probability to the 5^{th} item compared to the novel backward layout (*BF* = 2.62 x 10^3).

Kendall's correlations were run to investigate the link between this pattern of looking at the 7^{th} item during the 1000ms retention period and trial accuracy, using the average values per participant and per trial. There was no correlation between fixation probability to the 7^{th} presented item in the novel-static condition in forward order and trial accuracy (τ = .07, p = .39), and also no correlation between the novel-static condition in backward order and trial accuracy (τ = .001, p = .85). There was also no correlation between fixation probability to the

7th presented item in the typical layout in forward order and trial accuracy (τ = -.08, p = .55), and also no correlation between the typical layout in backward order and trial accuracy (τ = .02, p = .83).

Kendall's correlations were run to investigate the link between looking at the 5th item during the 1000ms retention period and trial accuracy, using the average values per participant and per trial. There was a weak negative correlation between fixation probability to the 5th presented item in the novel-static condition in forward order and trial accuracy (τ = -.06, p = .01), and no correlation between the novel-static condition in backward order and trial accuracy (τ = .03, p = .93). There was also no correlation between fixation probability to the 5th presented item in the typical layout in forward order and trial accuracy (τ = -.08, p = .06), and a weak negative correlation between the typical layout in backward order and trial accuracy (τ = -.06, p = .04).

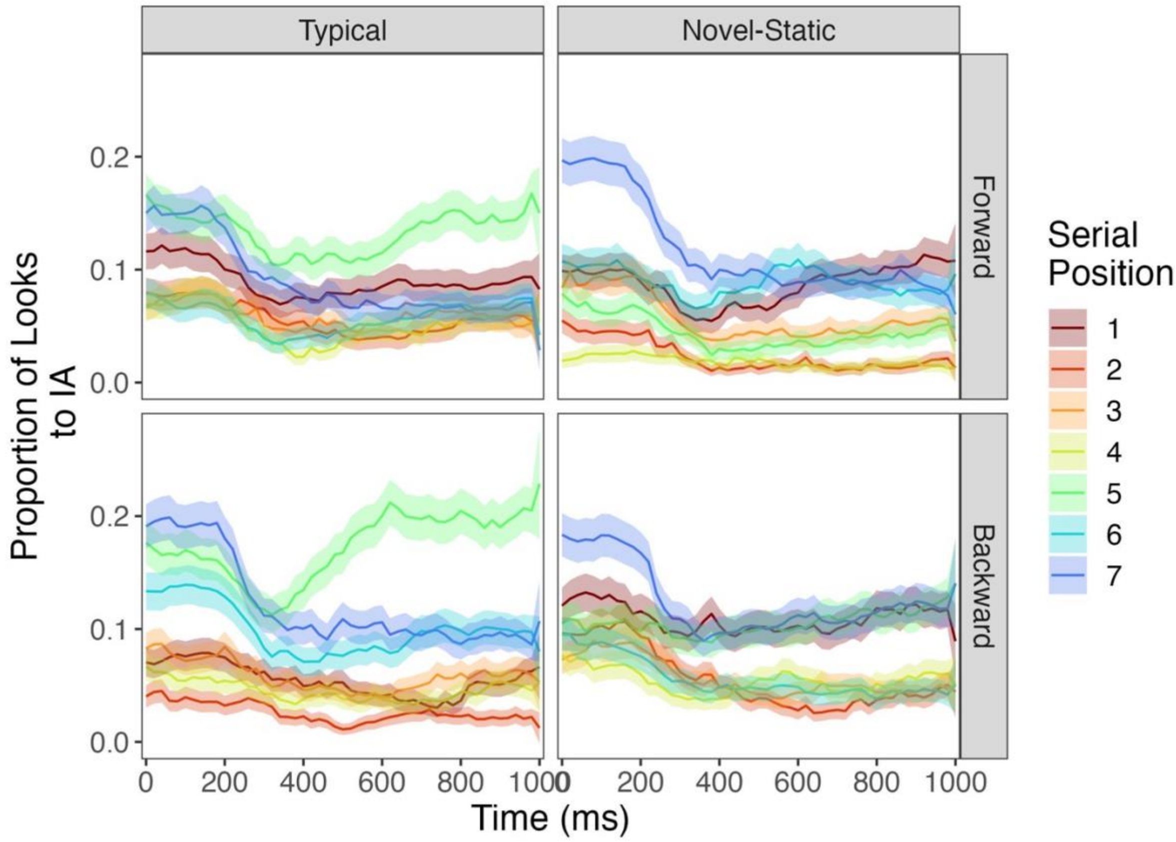

Figure 3.11 Time course of the proportion of looks to each digit interest area as a function of layout (novel-changing and typical) and recall order (forward and backward) during the retention interest period. Shaded areas represent within-participant standard errors around the mean calculated with the Cousineau-Morey method.

3.3.2.6 Saccade Amplitude during Retro Cue Periods

To investigate the saccade amplitude during the retro cue periods (1-3; illustrated in Figure 3.12; note these are after the retention period as illustrated in Figure 3.7), a three-way Bayesian ANOVA was run including the main effects of layout, order, and interest period (Table 3.1). As the results indicate strong evidence against omitting the main effect of interest period, each of the periods was followed up separately. In the first retro cue period, the best model included a main effect of layout (*BF* = 99.63), which was preferred over the full model with a *BF* of 29.37 and over a model including the main effects of layout and order with a *BF* of 3.78. Following up, excluding novel-static condition from the analysis revealed a significantly higher saccade amplitude in the typical compared to the central layout conditions (*BF* = 125.03). Excluding the central layout condition from the analysis revealed no evidence for a difference between the typical and novel-static keypad conditions, with the best model including order barely preferred over the null with a *BF* of 0.26.

A 3x2 Bayesian ANOVA investigating the second retro cue period revealed that the best model included a main effect of layout (BF = 5.19). The best model was preferred over a model including the main effect of layout and order with a BF of 5.51. Following up, excluding the novel-static condition from the analysis revealed a significantly higher saccade amplitude in the typical compared to the central layout conditions (*BF* = 19.09). Excluding the central layout condition from the analysis revealed no evidence for a difference between the typical and novel-static keypad conditions, with the best model including order barely preferred over the null with a *BF* of 0.47.

Analysis of the third retro cue period with a two-way BANOVA including layout and order revealed that the best model contained only the main effect of order, with higher saccade amplitude in the forward order compared to the backward order condition (*BF* = 146.60). There was moderate evidence for the exclusion of the main effect of layout and the interaction (*BF* = 8.01).

Table 3.1

Bayesian ANOVA Results Saccade Amplitude during each of the three retro cue periods (including 500ms of cue presentation and 2000ms of blank display) as a function of order (forward or backward) and layout (central, novel-static, typical).

Omit Predictor from full model	**BF**
Interest Period	6.50×10^{-12}
Layout	0.02
Order	0.29
Interest Period x Layout	0.57
Interest Period x Order	2.37
Interest Period x Layout x Order	6.70
Layout x Order	13.55

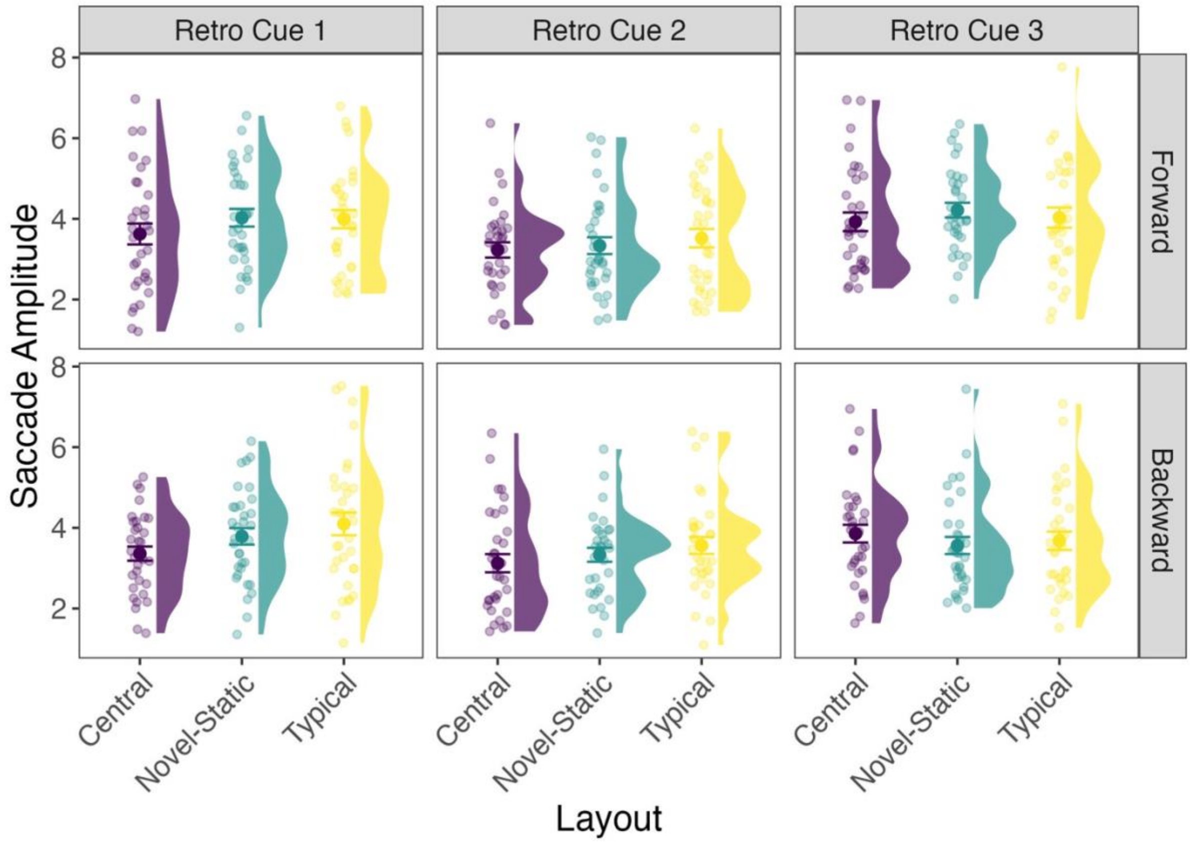

Figure 3.12 Mean saccade amplitude in visual degrees for each layout condition (central, novel-static, typical), recall order (forward, backward) during the retro cue periods (1-3), each of which included a 500ms display with the retro cue and a 2000ms blank display. Error bars show one standard error around the overall mean per condition. Points represent participant-specific means. Density curves along the continuous axis reveal data distribution and density across conditions.

3.3.2.7 Time course of Fixation Probability during Retro Cue Periods

Proportion of looks to each serial position item during each of the retro cue periods (including the 500ms retro cue display and a blank 2000ms display; note these periods are different from the retention period and takes places after it) as a function of condition (typical-forward, typical-backward, novel-static-forward, and novel static-backward) is illustrated in Figure 3.13.

A three-way ANOVA was run with condition (typical-forward, typical-backward, novel-static-forward, and novel static-backward), interest period (retro cue 1-3), and serial position (1-7). As there are 18 effect combinations, evidence for omitting each effect from the full model is reported in Table 3.2, which shows evidence for keeping the main effect of serial position and condition, alongside the interaction effect between them.

For consistency with the previous analysis of the retention period (Figure 3.11), the current analyses focused on the fixation probability of the 5th and 7th item separately and averaged across the three retro cue interest periods. A higher fixation probability to the 7th item was found throughout the retro cue periods in the typical-backward compared to the typical-forward condition (*BF* = 997.80). However, there was no statistically significant differences found between the fixation probability to the 7th item in the novel-static-forward and novel-static-backward conditions. The same values were higher in the typical-forward compared to the novel-static-forward condition (*BF* = 2.93×10^5).

Considering only the probability of fixating the 5th item, there was no clear evidence for a significant difference between the typical-forward and typical-backward conditions (*BF* = 1.81). There was decisive evidence for higher fixation probability of the 5th item in the novel-static-forward condition compared to the novel-static-backward (*BF* = 4802.324). There was also a higher probability of fixating the 5th item in the typical-forward condition compared to the novel-static-forward condition (*BF* = 85372.88). There was strong evidence for higher fixation probability to the 5th item in the typical-backward compared to the novel-static-backward condition (*BF* = 16.31).

Kendall's correlations were run to investigate the link between this pattern of looking at the 5th item during retro cue period and trial accuracy, using the average values per participant and per trial. There was no correlation between fixation probability to the 5th presented item in the novel-static condition in forward order and trial accuracy (τ = -.04, p =

.48), and also no correlation between the novel-static condition in backward order and trial accuracy (τ = -.012, p = .82). There was also no correlation between fixation probability to the 5th presented item in the typical layout in forward order and trial accuracy (τ = -.08, p = .49), and there was a weak negative correlation between the typical layout in backward order and trial accuracy (τ = -.09, p = .01).

Kendall's correlations were run to investigate the link between looking at the 7th item during the retro cue period and trial accuracy, using the average values per participant and per trial. There was a weak negative correlation between fixation probability to the 7th presented item in the novel-static condition in forward order and trial accuracy (τ = .08, p = .22), and no correlation between the novel-static condition in backward order and trial accuracy (τ = .013, p = .19). There was also no correlation between fixation probability to the 7th presented item in the typical layout in forward order and trial accuracy (τ = .03, p = .50), and a weak positive correlation between the typical layout in backward order and trial accuracy (τ = .08, p = .02).

Table 3.2

Bayesian ANOVA Results Fixation Probability during each of the three retro cue periods (including 500ms of cue presentation and 2000ms of blank display) as a function of condition (typical-forward, typical-backward, novel-static-forward, and novel static-backward).

Omit Predictor from full model	BF
Serial Position	7.24×10^{-131}
Serial Position x Condition	2.31×10^{-73}
Condition	9.48×10^{-13}
Serial Position: Interest Period	0.003
Interest Period	0.39
Serial Position x Interest Period x Condition	2149.12
Interest Period x Condition	119815.3

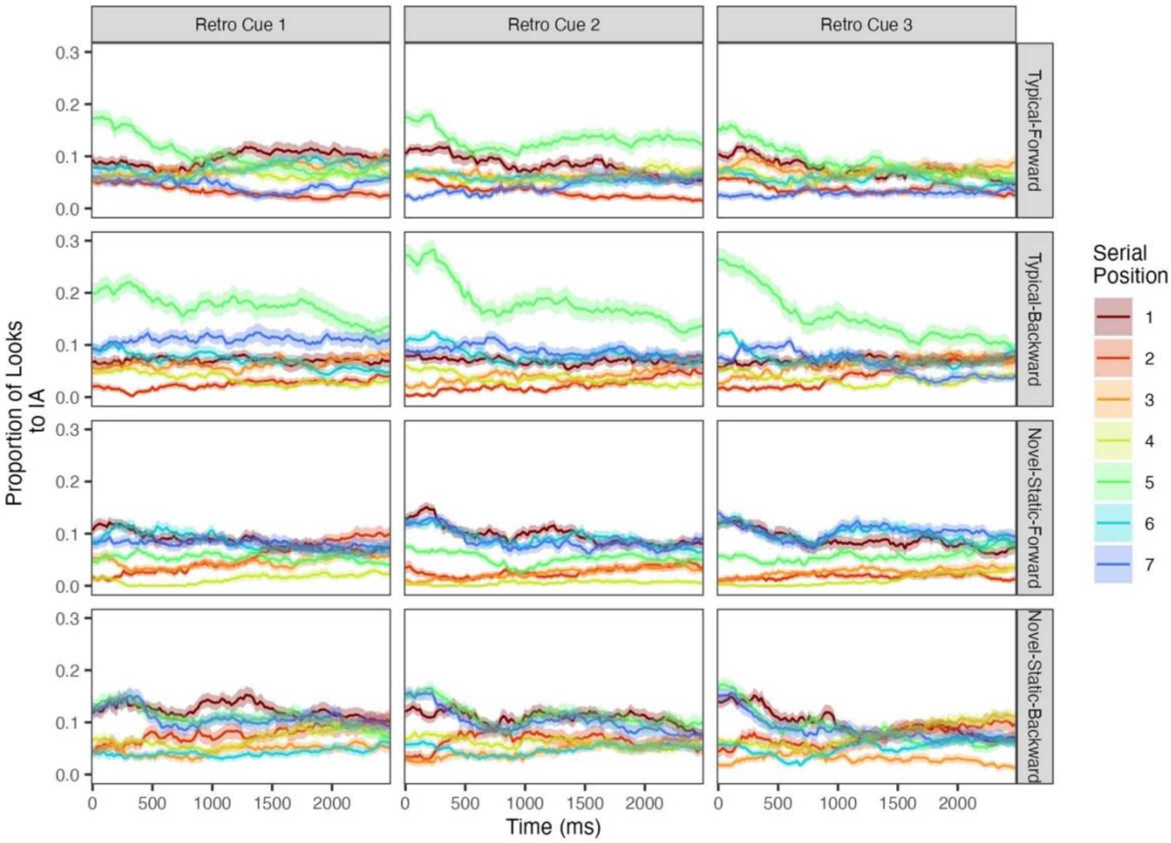

Figure 3.13 Time course of the proportion of looks to each digit interest area as a function of layout-order conditions (novel-static-forward, novel-static-backward, typical-forward, typical-backward) during each retro cue period (each including 500ms of cue presentation and 2000ms blank display). Shaded areas represent within-participant standard errors around the mean calculated with the Cousineau-Morey method.

3.3.3 Discussion

In the context of exploring the visuospatial bootstrapping (VSB) effect on working memory, Experiment 2 aims to investigate gaze during the encoding of digits and during their retrieval and maintenance. In Experiment 2 retro cues were incorporated to allow the cueing of one item at a time and the investigation of whether gaze was directed to the relevant item.

No significant differences were found in recall accuracy between novel and typical conditions within forward recall tasks. However, a notable VSB advantage emerged in the backward recall condition, characterized by enhanced recall accuracy for typical as opposed to novel-static conditions. This finding suggests a potential concentration of the VSB effect towards the end of the list, suggesting that initiating recall from the final segments may facilitate a more pronounced observation of this effect.

Previous research suggests that backward recall prompts a heightened reliance on visuospatial encoding mechanisms (Guitard et al., 2020; Miles et al., 1991; Watkins et al., 2000). This reliance may account for the observed VSB benefit in backward recall, suggesting that visuospatial representations are more robustly engaged and utilized when participants are tasked with reverse-order recall. Such findings align with Donolato et al. (2017), who highlighted the differential engagement of visuospatial representations in backward recall, offering a potential explanation for the enhanced recall performance in typical versus novel-static conditions within this paradigm. However, in terms of eye movements we find no clear evidence for a heightened reliance of visuospatial representations in backward compared to forward recall.

The current findings revealed lower saccade amplitude in the central condition compared to the typical and novel-static keypad conditions during the presentation and retention periods, similar to the pattern observed in Experiment 1. They also replicated findings from Experiment 1 indicating lower probability of fixating incoming items in the typical and novel-static conditions compared to the central condition. However, in Experiment 2 no clear pattern of higher cumulative looking during the presentation period in the typical compared to the novel-static condition was observed. This could be due to the introduced methodological changes such as the spacing out of the stimuli or the introduction of a static rather than dynamic spatial configuration. However, if learning of the spatial configuration throughout the session occurred in the novel-static condition this would be reflected in an accuracy boost not only in the forward but also in the backward recall. If learning took place, then accuracy should be enhanced for later trials within the novel-static blocks. However, we failed to find a significant difference between accuracy for the first-presented half of trials and the remaining trials within the novel-static blocks (p = .33), suggesting that no learning of the novel layout took place. Further, a clear link between these eye movement patterns and performance was not found.

Analysis of the 1000ms retention period showed that there was a pronounced probability of fixating the interest area of the seventh presented item which was observed in both the typical and novel-static layout conditions. This contrasts with findings in Experiment 1 of higher fixation probability to the interest area of the last item in the typical compared to the novel-changing keypad layout. Again, this could reflect familiarity with the novel-static layout which may result in flexible and strategic revisiting of the interest area of the last item. Analysis of the 1000ms retention period also revealed that backward recall in both typical and novel layouts resulted in higher probabilities fixating the fifth item compared to forward sequences. Additionally, the typical layout was associated with higher fixation probabilities to the fifth item compared to the novel layout, both in forward and backward sequences. These findings could be interpreted as the long-term memory representations of the typical keypad affording strategic revisiting of key locations. Interestingly, the final memory retro cue for the typical forward condition and the first retro cue in the typical backward condition were selected from the fifth, sixth, and seventh serial position, and the increased probability of fixating the fifth item might be indicative of preparing or rehearsing the first interest area of the last-presented memory chunk. However, either weak or no correlation was found between these patterns of revisiting the fifth and seventh items and recall accuracy, which suggests that any functional utility of this behaviour does not directly translate to improved recall.

3.4 General Discussion

Data clearly show that eye movements differ when encoding verbal information that has a familiar layout compared with the same verbal information presented in a novel layout. These differences in gaze pattern could be taken as the recruitment of oculomotor infrastructure to apply a spatial rehearsal strategy, in which eye movements are used to re-activate the positions of previously viewed items, and this positional information can presumably only possibly benefit recall in the typical keypad condition where the positions map to learned digits. However, if these gaze patterns are considered evidence of visuo-spatial rehearsal, then it must be concluded that gaze patterns are not impacting performance strongly because more looking was not correlated with better recall in any conducted analyses. Possibly, looking back towards the position of a to-be-remembered item serves to attempt to trigger retrieval of unknown items and the stochasticity of this process hinders detecting a benefit. Nonetheless, observing different gaze patterns with the typical compared to novel keypad layout implies that the familiar mappings, which are the only thing differing between these scenarios, indeed change participants’ approach to the task. Baddeley et al. (2021) suggest that a visuospatial component of the multiple-component working memory system ought to be considered more dependent on executive resources than the verbal component is believed to be, based on consistent findings that visuospatial memory is impacted more by dual-task interference than verbal memory (e.g., Morey, 2018; Morey et al., 2013; Morey & Mall, 2012). Analysis of effects of gaze on recall in a task where spatial support should be beneficial is consistent with this idea. If domain-specific support from the oculomotor system is affecting recall, the impact is smaller than what can reliably be detected and possibly quite short-lived. These severe limits on the extent to which eye movements might support spatial memory suggest that additional support would be required for successful maintenance in most cases. Regardless, the observation of different patterns of gaze for the typical layout are consistent with the view that this known spatial mapping is used to augment verbal recall, even if the eye movements themselves do not directly support memory. Overall, this result seems most consistent with the assumption that domain-specific resources can be brought together to influence and augment immediate memory but offers little support for the idea that the oculomotor system supports robust and sustained serial spatial rehearsal.

An investigation into visuospatial bootstrapping revealed unique patterns of eye movements during the encoding and retention phases providing further insight into the cognitive processes involved in processing spatially-arrayed verbal items. Findings demonstrated the occurrence of regressions to previously presented items during the encoding stage, suggesting a refinement of mental representations based on their spatial arrangement. During the retention interval in Experiment 1, a distinct increase in gaze towards the last presented item was observed. In Experiment 2, while a VSB effect was found in backward but not in forward recall, differences in gaze shifts were found between the typical and novel-static conditions. Specifically, in novel-static layout conditions a bias towards the last-presented item was observed and in the typical layout a bias towards the last-item and also the fifth item was found, which might be indicative of preparing or rehearsing the first interest area of the last-presented memory chunk. This bias in attention during the maintenance phase in both experiments implies a dynamic engagement with the memorized spatial array, possibly indicative of privileged treatment of the later-presented items. Findings of different eye movement patterns during verbal encoding, although with no direct links between those eye movements and recall, prompts a more nuanced consideration of the functional role of eye movements in the visuospatial bootstrapping process. Future research may benefit from exploring potential moderating factors that could elucidate the limitations and boundaries of the observed eye movement patterns. Additionally, an examination of individual differences in the susceptibility to the influence of eye movements on encoding and recall may contribute valuable insights, further refining our understanding of the variability in cognitive strategies that may augment recall in verbal tasks. The current study adds to the growing body of literature on visuospatial bootstrapping and sets the stage for more nuanced inquiries into the specific roles played by eye movements in the encoding and retrieval of spatially organized verbal information.

4 Eyes on Memory and Action: Investigating Gaze during Encoding and Maintaining of Verbal and Spatial Information

4.1 Introduction

Working memory serves both the past and the future, as relevant information is selected from the internal space of memory to prepare and execute an action. For example, when preparing to make tea, memory representations of the necessary items and steps aid us in selecting relevant items in our environment to execute the needed actions in the correct order. Eye movement research has revealed that both our internal space of memory and our attention can be influenced by both memory (Czoschke et al., 2019; Souza & Oberauer, 2016; van Ede et al., 2019, van Ede et al., 2024) and the requirements of impending actions (Baldauf & Deubel, 2008; Ohl & Rolfs, 2017; Rolfs et al., 2011; Stewart et al., 2019).

Visual working memory is suggested to be biased towards action-relevant information and that its main function is to facilitate goal-directed actions (for a review, see Heuer et al., 2020). Research investigating the effects of action on the maintenance in visual working memory have mainly used dual-task paradigms in which participants had to complete a movement task which had no predictive value for the memory task, with each item in memory being equally likely to be tested irrespective of the goal location or type of movement. These tasks have revealed that items presented at the action goal are prioritised irrespective of memory cue validity and even if these are unlikely to be probed (Ohl & Rolfs, 2017, 2020). Further, goal-oriented saccadic selection occurs independently of memory load (Ohl & Rolfs, 2020).

Recent studies have shown that performing eye movements directed towards goals after initially encoding visual information can improve the recall of memory items positioned in alignment with these eye movements. In other words, memory recall is enhanced for items situated at the intersection of where they were memorized and where subsequent action-oriented gaze is directed (Hanning et al., 2016; Hanning & Deubel, 2018; Ohl & Rolfs, 2017, 2018). This demonstrates that the coordination between where we look and where we plan to look plays a crucial role in strengthening memory for spatial information. These findings provide strong evidence for the view that visual working memory is biased towards selecting information relevant to the required action. Indeed, a large body of research supports this view (e.g. Aagten-Murphy & Bays, 2018; Allport, 1987). The process of memorizing the locations of visual stimuli triggers eye movements towards these locations, showcasing the oculomotor system's involvement in spatial memory tasks (Olsen et al., 2014; Wynn et al., 2018). Further, the disruption of eye movements during the memory retention phase impacts visual-spatial memory (Lawrence et al., 2004; Ohl & Rolfs, 2020; Postle et al., 2006; Tremblay et al., 2006), with evidence for enhanced memory when free view is allowed during the retention interval (e.g. McAteer et al., 2023; Pearson et al., 2014; Souza et al., 2020; Williams et al., 2013). However, a study by Loaiza and Souza (2022) failed to find a clear effect linking fixations under spontaneous conditions and recall. This is also in line with findings presented in the previous chapters.

Van Ede (2020) extends this view of selection-for-action and notes the bi-directional influence between visual working memory and actions. Saccade trajectories have been shown to be involuntarily influenced by the contents of visual working memory in dual-task settings, with goal-directed eye movements curving away from the location of an item that is held in visual working memory concurrently with the secondary saccade task (Belopolsky & Theeuwes, 2011; Boon et al., 2014; Theeuwes et al., 2005). This finding suggests that oculomotor behaviour is influenced by what is in memory and what action output is required. Studies that investigated eye movements in the absence of visual capture probe or secondary-tasks have revealed that fixational eye movements are biased towards the memorized location of the selected memory item (van Ede et al., 2019). A growing body of research investigating microsaccades has indeed found that they can be used to track working memory selection through spatial locations (e.g. de Vries et al., 2023; de Vries & van Ede, 2024; Liu et al., 2022; van Ede et al., 2019). Taken together, these studies suggest that looking behaviour during information maintenance is influenced by both memory and action preparation, but the different factors that influence these gaze biases are still not well understood.

Research highlights distinct patterns of eye movement during the encoding and maintenance phases of verbal versus visuospatial information. Studies by Czoschke et al. (2019) revealed differential oculomotor behaviours, with verbal encoding eliciting more precise eye movements towards to-be-remembered items, in stark contrast to the encoding of spatial information, where such targeted saccades were less frequent. Interestingly, during the latter stages of encoding, fixations on locations previously holding items were more pronounced in spatial tasks, correlating with enhanced spatial memory performance. This suggests a more significant role of oculomotor activity in maintaining spatial information compared to verbal information. Further exploration by Staudte and Altmann (2017) supports these findings, demonstrating fewer eye movements towards previously item-containing locations during verbal retrieval tasks compared to spatial retrieval tasks. This pattern indicates a nuanced relationship between oculomotor behaviour and the maintenance of different types of information, with verbal information seemingly requiring less direct visual engagement for its maintenance. Verbal information is suggested to benefit from both domain-specific and general working memory resources, with distinct mechanisms for maintenance identified: an articulatory process linked to language production and a more general attention-based mechanism (Camos et al., 2009; Camos & Barrouillet, 2014; Hudjetz & Oberauer, 2007). These mechanisms, operating independently, highlight the complex interplay between attention, eye movement, and memory maintenance, particularly for verbal information. Verbal working memory's articulatory and attention-based maintenance mechanisms suggest a more flexible engagement with cognitive resources, potentially explaining the observed weaker link between eye movements and verbal memory maintenance compared to spatial memory. To provide a better insight into these potential differences, the current study investigated how gaze shifts across time when encoding and maintaining verbal and spatial information.

As investigated in the previous chapters, another factor that can influence eye movements is the recall order direction. Studies indicate that participants adapt their strategies to meet task demands (Guitard et al., 2020; Miles et al., 1991; Watkins et al., 2000). For example, in a digit recall task, Guitard et al. (2020; Experiment 5) found that manual-spatial tapping (established as having a detrimental effect on spatial representations) at recall was detrimental to digit recall in backward but not in forward order. This suggests that phonological encoding is preferred when preparing for forward recall, whereas visuospatial encoding is favoured for backward recall. Miles et al. (1991) found detrimental effects of playing irrelevant speech at both input and output in a letter recall task; however, the introduction of articulatory suppression in addition to the irrelevant speech removed the previously observed detrimental effect of irrelevant speech. Furthermore, Watkins et al. (2000; Experiment 3) found that common words were found to be more recallable than rare words when no warning of the memory test was given.

It has been observed that visuospatial strategies play a more significant role in backward recall compared to forward recall, particularly at the retrieval stage. This is evident in verbal span tasks, where performance on backward recall tends to be inferior to forward recall, although this trend is not always seen in visuospatial tasks (for a review, see Donolato et al., 2017). To manage this, participants might visualize the sequence of items and, depending on the recall order, either sequentially navigate through this mental image or employ mental rotation strategies to reorder the items for recall (e.g. Li & Lewandowsky, 1995; St Clair-Thompson & Allen, 2013).

This research to answer the following main question:

- Are there differences in memory-relevant and action-relevant gaze patterns during the encoding and maintenance of verbal versus spatial information?

In the present study, looking behaviour was investigated for verbal and visual information across two experiments by using a modified Corsi-block task and a digit recall task. To test visual working memory, squares were presented on one side of the screen and asked participants to recall the locations and order of the squares on the mirrored (other) side of the screen to prevent the overlapping of locations of memory items and planned action. Similarly, to test verbal working memory squares which contain digits on one side of the screen were presented and participants were asked to recall the digits in the correct order on the other side of the screen. The separation of the locations of the presented items and where they need to be recalled allows us to distinguish between memory-driven and goal-driven eye movements. Moreover, to investigate the effect of recall order direction on oculomotor activity, participants were asked to either recall the items in forward or backward order. In Experiment 1, participants were asked to recall the complete list of items, while in Experiment 2 a subset of items were retro-cued to allow a more detailed investigation where there is only one relevant item location at a time after each retro cue. Differences in the proportion of looks to memory-congruent and action-congruent interest areas across time would indicate different use of visuospatial strategies.

4.2 Experiment 1

4.2.1 Method

4.2.1.1 Participants

Twenty-three participants took part in the experiment. One participant was excluded due to poor eye tracking calibration and validation values (the mean spatial accuracy was worse than 0.5 degree or a maximum spatial accuracy worse than 1 degree for each performed validation procedure). The remaining participants (8 female, 2 non-binary) ranged from 18-28 (M=20.57, SD= 2.58). All participants were students at Cardiff University and were recruited via the School of Psychology's participant panel, social media and word of mouth. All had normal or corrected-to-normal vision. No statistical methods were used to pre-determine sample size but the sample size was chosen to be similar to that of previous studies investigating similar measures ranging between 20 and 30 participants (Czoschke et al., 2019; van Ede et al., 2019).

4.2.1.2 Apparatus

Experiment Builder (SR Research) was used to administer the task on a monitor with a width of 53.2cm, height of 30cm and refresh rate of 60Hz. An SR Research EyeLink 1000 Plus eye tracker was used to record eye movements at a sampling rate of 1000Hz using pupil and corneal reflection, tracking both eyes of the participants. A chin and forehead rest was used to minimise head movements which might lead to impairment of the quality of eye tracking data. A 9-point calibration and validation grid were used to fit and test the spatial accuracy of the eye tracker before each block in the experiment. If the spatial accuracy during validation was worse than 1 degree or the maximum accuracy was worse than 2 degrees, calibration and validation were repeated. Drift check before each trial monitored the spatial accuracy, with more than three checks with error worse than 1 degree prompting the calibration and validation procedures to be repeated.

4.2.1.3 Materials

Two memory lists were used for this study. One containing 96 combinations of 7 locations randomly drawn from a 4x7 grid (see Figure 4.1) with one location per grid row. The second memory list contained 96 combinations of 7 digits randomly drawn from 0-9 without repetition of digits per combination. The recall screens consisted of either a 4x7 grid of squares, each with a width and height of 80 pixels and 60 pixels apart from each other or of the digits (Times New Roman font with a size of 40) 0-9 in squares 80 pixels high and wide. The background throughout the experiment was mid-grey (RGB: 153,153,153,255).

4.2.1.4 Design

The combinations of the task type (square or digit recall), side of presentation area and recall area of the display (left and right side of the screen, or right and left side of the screen), and cue order direction (forward or backward) were blocked (eight blocks in total) and randomised across participants. All participants took part in all conditions within a single session.

4.2.1.5 Procedure

Participants were tested individually in a dimly illuminated room. They were asked to remember a sequence of seven locations of squares or seven digits and recall them in forward or backward order. Participants completed eight practice trails, which were then followed by 96 experimental trials (12 trials per block) with instructions before each block informing the participant of the task type, side of presentation and recall area, and cue order direction. The session lasted approximately 1 hour and breaks were possible between blocks and trials.

Each trial began with a drift check which needed to be accepted by the experimenter, followed by a blank display for 250ms. Seven memory items (empty blocks or blocks containing a digit) were then presented on either the left or right side of the screen (Figure 4.1), each for 1000ms with an 250ms inter-stimulus interval. A blank screen for retention was then presented for 5000ms. The recall screen was then presented, showing either the square grid for the block recall task or the digits (0-9) in two rows until the end of the 7th mouse click.

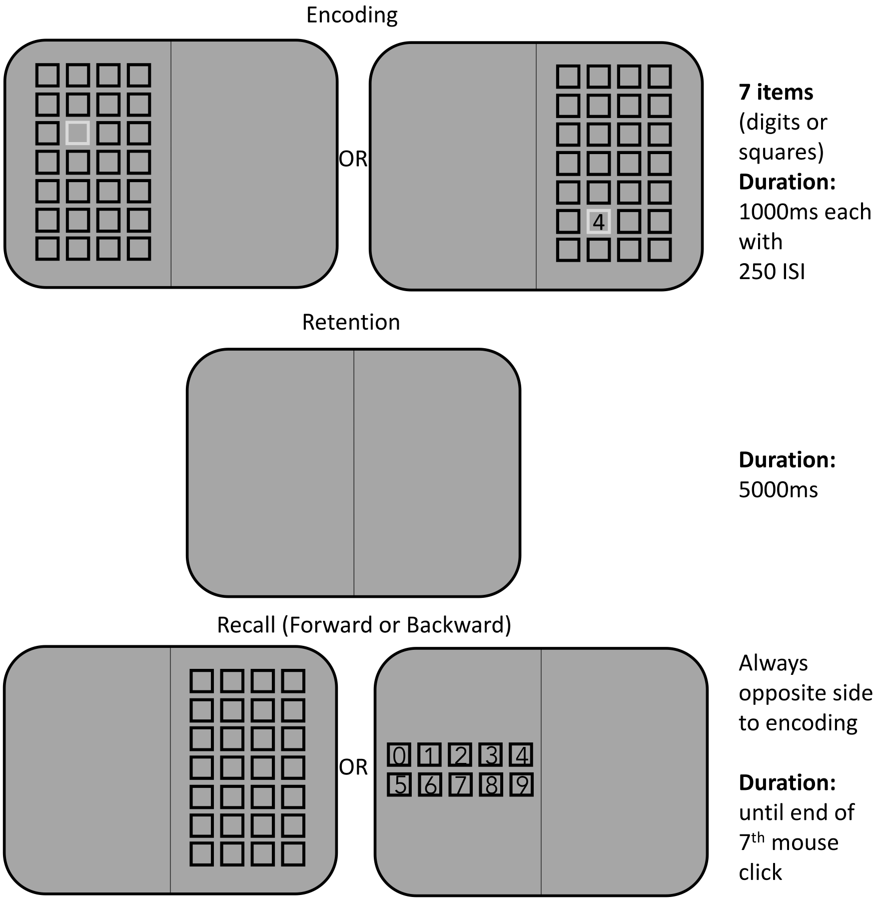

Figure 4.1 Trial sequence for Experiment 1, showing examples of encoding, retention, and recall displays.

4.2.2 Results

4.2.2.1 Data Analysis

For the analysis, recall accuracy underwent arcsine transformation, and all measures of eye movement were log-transformed to meet the assumptions required for Linear Mixed Models (LMM). To explore patterns of gaze during encoding, interest areas (IAs) were established measuring 130 x 130 pixels, with the centre of each IA being the centre of all possible square locations. For investigating the time course of gaze during the retention interval, two IAs were 910 pixels vertical by 520 pixels horizontal, each centred at the middle of the left and the middle of the right of the display containing all possible encoding items. The interest area that aligned with where the items were presented will be referred to as the memory interest area, while the other interest area will be referred to as the action interest area. the proportion of gaze directed at an IA was then assessed by averaging the gaze samples recorded from both eyes at 100ms intervals. In addition to evaluating accuracy in recall, various metrics related to eye movement were examined. The extent of saccade movements, or saccade amplitude, was analysed as an indicator of the level of oculomotor activity, with larger amplitudes indicating saccades covering longer distances. The probability of looking at displayed IAs and the frequency of gaze returning to IAs that had been previously memorized were also considered, to understand the focus of eye movements.

The analyses of recall accuracy, saccade amplitude, and probability of looks during encoding were conducted using the lmer function from the lme4 package (Bates et al., 2015) within the R software environment (The R Foundation for Statistical Computing, Version 4.3.2). The coefficients (β values), standard error (SE) values, t-values, and p-values for each metric were reported, with the p-values being calculated using the lmerTest library for LMMs (Kuznetsova et al., 2017). For effects that did not reach significance ($p <.05$), only t and p values were reported without β or SE values, and these effects were not emphasized in interpretations. When the full model failed to converge, suggesting possible overparameterization or insufficient data, initially the structure of random effects was modified by setting all covariance parameters to zero. If problems with estimation continued, slope variables approaching zero were sequentially eliminated until the model converged (Bates et al., 2015). The details of the final, simplified model structure will be clearly described.

The statistical analysis of gaze patterns over time employed a cluster-based permutation method (Maris & Oostenveld, 2007), which is effective for evaluating physiological effects across multiple data points, such as time-series data from eye-tracking. This method involves three steps: forming clusters of significant sample points, calculating statistics for each cluster, and then comparing these statistics to a reference distribution generated through Monte Carlo simulations that randomly assign condition labels to the experimental data. This approach allows us to assess the likelihood of observing the differences between conditions by chance. To incorporate LMM analyses into cluster evaluations, the clusterperm.lmer function was used from the permutes package in R (Voeten, 2021), which calculates the null distribution by permuting data within regression models that include random effects, based on the Likelihood Ratio Test (LRT). The permutation count was set to 10,000 for each test and applied a two-sided alpha level of .05. Furthermore, clusters with a size smaller than 100 were considered as negligible. A larger cluster mass indicates a more significant effect or difference between conditions over the cluster, suggesting that the observed differences are consistent and not merely due to chance. Kendall's tau correlation analysis (Kendall, 1948) was selected to explore the relationship between trial accuracy and average fixation probabilities to the action interest area due to its suitability for ordinal data and its robustness against non-normal distributions. Unlike Pearson's correlation, which assumes linear relationships and normally distributed data, Kendall's tau is a non-parametric measure that assesses the strength and direction of association between two variables based on the ranks of data rather than the raw data values. This makes it ideal for handling datasets with ordinal or non-linear relationships.

4.2.2.2 Recall Accuracy

To consider the influence of recall and order conditions on recall accuracy (Figure 4.2), a Linear Mixed Model (LMM) was conducted. The maximal model included trial accuracy as a dependent variable and recall condition (digit, which was contrast coded as 1, and square, which was contrast coded for -1) and order condition (backward, which was contrast coded as 1, and forward, which was contrast coded for -1) as categorical fixed factors. Participant was included as a random factor with random intercepts and slopes. The model resulted in a significant effect of recall condition ($b = .268$, $SE = .023$, $t = 11.84$, $p < .001$), with trial recall accuracy significantly higher in the digit conditions ($M = .67$, $SD = .31$) compared to square conditions ($M = .28$, $SD = .22$). The model also revealed a significant effect of order condition ($b = -.039$, $SE = .008$, $t = -4.56$, $p < .001$), with trial accuracy significantly higher in the forward ($M = .51$, $SD = .34$) compared to the backward conditions ($M = .44$, $SD = .31$). The interaction was also significant ($b = -.052$, $SE = .011$, $t = -4.63$, $p < .001$).

To further investigate this interaction, the digit and square conditions were considered separately. In the square conditions, there was no significant difference between the trial accuracy in forward and backward order conditions ($t = 1.08$, $p = .29$). However, in the digit recall conditions, trial accuracy was a significantly higher in the forward ($M = .74$, $SD = .28$) compared to backward ($M = .60$, $SD = .32$) order conditions ($b = -.091$, $SE = .016$, $t = -5.84$, $p < .001$). For a graph showing a lenient scoring of the square conditions, please refer to Figure 2 in the Appendix.

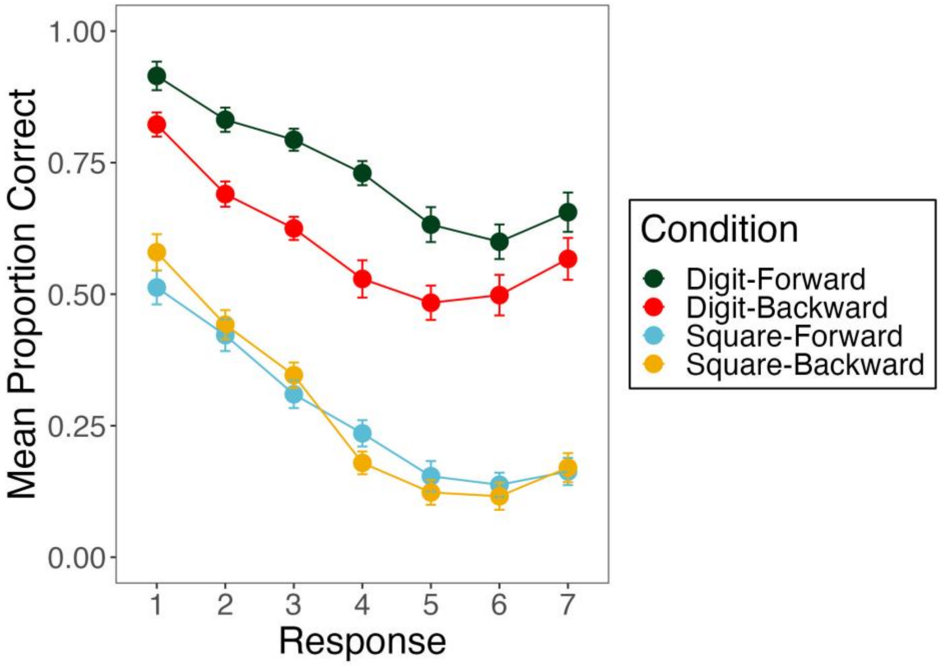

Figure 4.2 Mean proportion correct as a function of condition (central, novel-changing, typical) and response (1-7). Error bars mark within-participant standard errors around the mean calculated with the Cousineau-Morey method.

4.2.2.3 How much oculomotor activity occurred during encoding and retention?

To investigate saccade amplitude during encoding and retention (Figure 4.3), two Linear Mixed Model (LMM) were utilized. In this analysis, saccade amplitude during the encoding period in visual degrees served as the dependent variable, while recall condition (digit or square) and order condition (forward or backward) were used as categorical fixed factors. The model also incorporated random intercepts and slopes. The model revealed a significant effect of recall condition (b = .015, SE = .005, t = 2.91, p = .008), with significantly higher saccade amplitude in the digit (M = 4.98, SD = .96) compared to the square condition (M = 4.68, SD = 1.38). There was no significant effect of order condition (t = 0.88, p = .39). The analysis also explored the interaction effect between the variables, which was found not to be statistically significant (t = -1.59, p = .13). Another model was run to investigate saccade amplitude during the retention interval, revealing no significant effects of recall condition (t = 2.02, p = .056), order condition (t = -.70, p = .49), or their interaction (t = .07, p = .95).

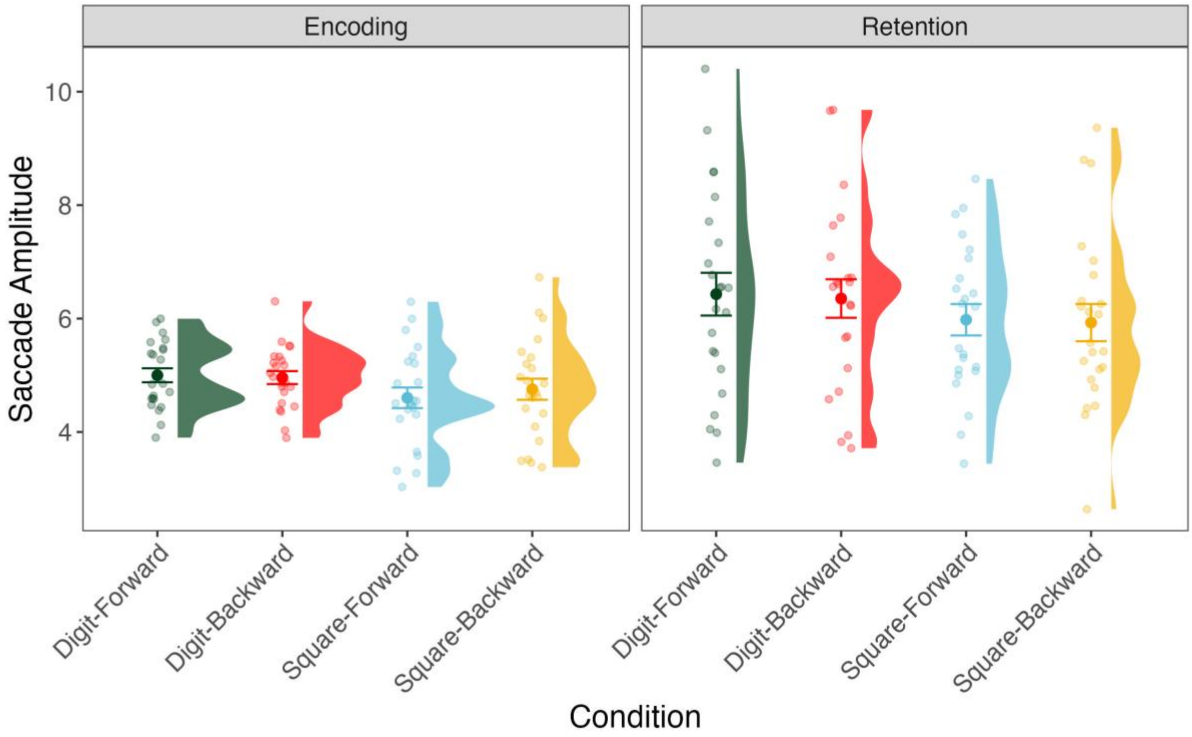

Figure 4.3 Mean saccade amplitude in visual degrees for each condition during the encoding and retention periods. Error bars show one standard error around the overall mean per condition. Points represent participant-specific means. Density curves along the continuous axis reveal data distribution and density across conditions.

4.2.2.4 What was fixated during encoding?

To examine the impact of recall and order conditions on fixation probability to presented items (Figure 4.4), a Linear Mixed Model (LMM) was conducted. This model used trial accuracy as the outcome variable, with recall condition (digit, coded as 1, and square, coded as -1) and order condition (backward, coded as 1, and forward, coded as -1) serving as categorical fixed factors. Additionally, random slopes for both task type and recall were included within participants but without their interaction term. The model resulted in a significant effect of recall condition (b = .028, SE = .003, t = 11.17, p < .001), with fixation probability to the presented item significantly higher in the digit conditions (*M* = .47, *SD* = .11) compared to square conditions (*M* = .31, *SD* = .13). The model also revealed a significant effect of order condition (b = .004, *SE* = .001, t = 2.85, p = .009), with higher fixation probability to the presented item in the backward (*M* = .40, *SD* = .14) compared to forward condition (*M* = .38, *SD* = .15). The interaction between the recall and order conditions was also significant (b = -.003, *SE* = .006, t = -5.34, p < .001).

To further investigate this interaction, the digit and square conditions were considered separately. In the digit recall conditions, there was no significant difference found between the forward and backward order conditions (t = .438, p = .61). In the square conditions, there was a significant difference between fixation probability to the presented item in forward and backward order conditions (b = .007, *SE* = .001, t = 7.132, p < .001), with significantly higher values in the backward (*M*= .33, *SD* = .13) compared to forward order condition (*M*= .29, *SD* = .12).

A Kendall's tau correlation analysis was undertaken to explore the connection between trial accuracy and average fixation probabilities to presented items across conditions. The results showed no statistically significant correlation for the digit-backward condition, τ = .085, p = .331, and the square-backward condition, τ = -.028, p = .576. No significant correlation was found in the digit-forward condition, τ = -.049, p = .097. However, a significant negative correlation emerged in the square-forward condition, τ = -.133, p = .002.

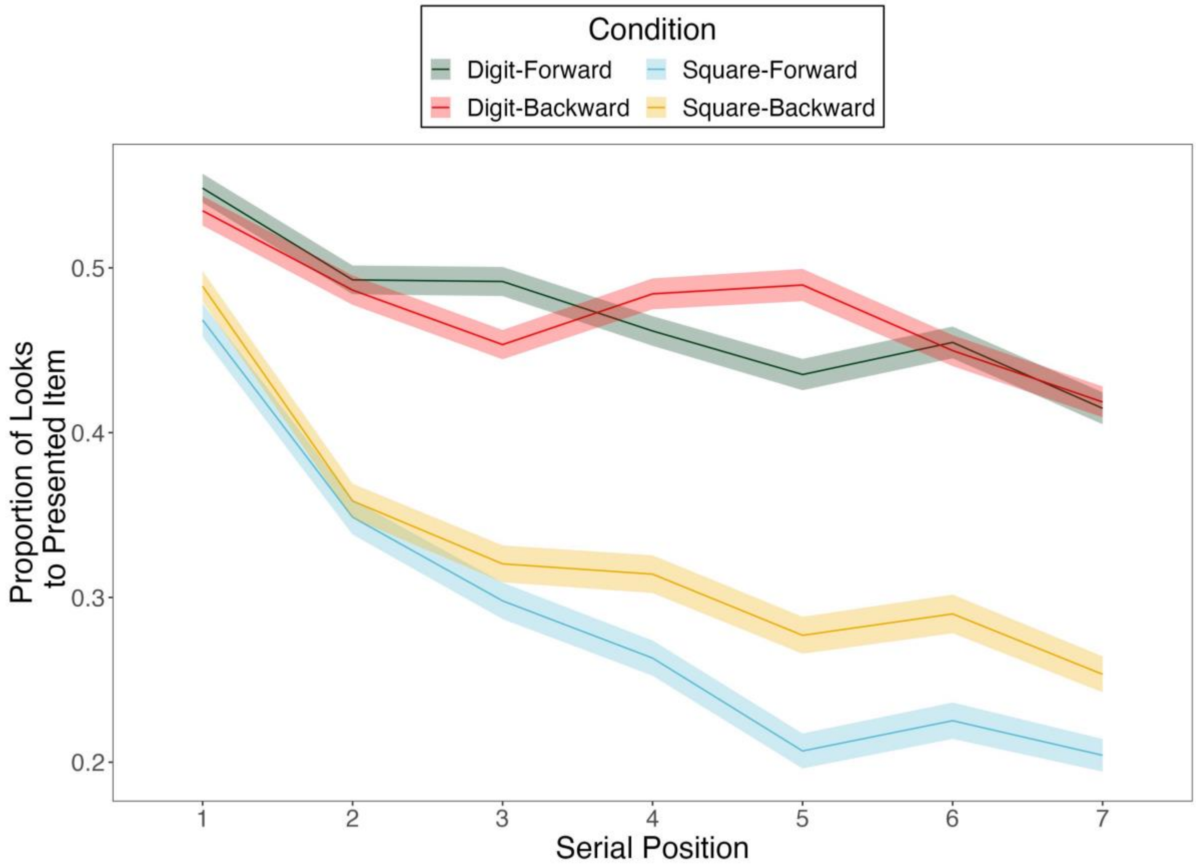

Figure 4.4 Mean fixation proportion of each of the on-screen items over time for each condition. Shaded areas represent within-participant standard errors around the mean calculated with the Cousineau-Morey method.

4.2.2.5 Did cumulative looks differ across conditions?

To investigate the effects of recall and order conditions on the cumulative probability of fixating the presented and previously presented items (Figure 4.5), a Linear Mixed Model (LMM) was run. The dependent variable in this model was cumulative fixation probability, while recall condition and order condition were included as categorical fixed factors. The model included random intercepts and slopes. There was a main effect of recall condition (b = .001, SE = .0002, t = 5.16, p < .001), with higher cumulative fixation probability in the digit (M = .58, SD = .13) compared to the square recall condition (M = .51, SD = .16). There was no significant effect of order condition (t = .86, p = .40). The interaction effect was also not significant (t = -.55, p = .58).

A Kendall's tau correlation analysis conducted to assess the relationship between trial accuracy and in cumulative fixation probabilities across recall condition (digit, square) and order condition (backward, forward). There was a weak negative correlation for the digit-forward condition ($\tau = -.163$, $p < .001$). However, no correlations were found between cumulative fixation probability and trial accuracy in the digit-backward condition ($\tau = -.026$, p = .11), in the square-backward condition (τ = -.045, p = .160) or in the square-forward condition (τ = -.022, p = .628).

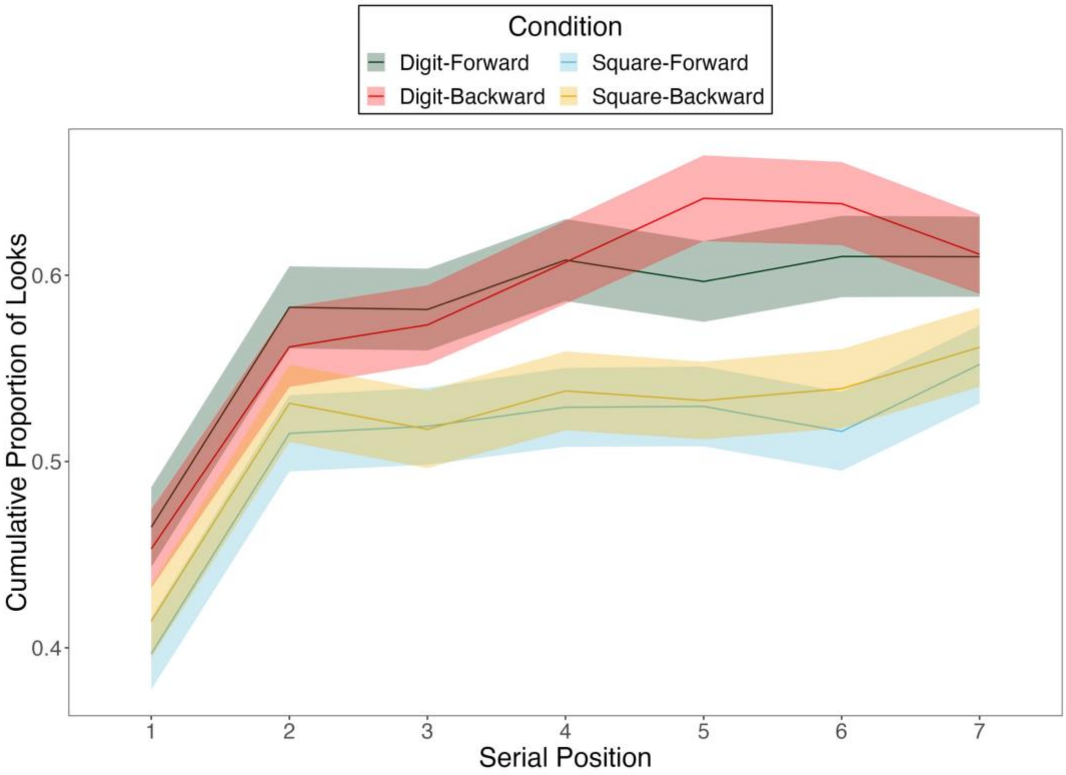

Figure 4.5 Mean proportion of samples to cumulative item locations as a function serial position (1-7) across each condition (digit-forward, digit-backward, square-forward, square-backward). Error bars mark within-participant standard errors around the mean calculated with the Cousineau-Morey method.

4.2.2.6 Was the memory interest area looked at during retention?

Proportion of looks to the memory interest area during the retention interval is illustrated in Figure 4.6 as a function of condition. A cluster-based permutation test was run based on a LMM with proportion of looks to the memory interest area as a predictor and with recall condition (digit, square) and order condition (forward, backward) as fixed effects, their interaction, and random intercepts and slopes for these effects across participants. The cluster-based permutation tests revealed a difference between the digit and square conditions between 0-3400ms (cluster mass = 1678.35, $p < .001$), a significant difference between the forward and backward conditions between 200 - 4300ms (cluster mass = 611.16, $p < .001$), and a significant interaction (cluster mass = 105.87, $p < .001$). To investigate the interaction, additional analyses were run on the digit and square recall conditions separately. The cluster-based permutation test revealed a significantly higher proportion of looks in the backward compared to the forward condition, both in the digit recall condition between 1700 - 2900ms (cluster mass = 130.22, $p < .001$) and in the square recall condition between 200 - 2900ms (cluster mass = 403.63, $p < .001$).

A Kendall's tau correlation analysis was undertaken to explore the connection between trial accuracy and average fixation probabilities the memory interest area across conditions. The results indicated a statistically significant negative correlation for the digit-backward condition ($\tau = -.152$, $p < .001$). A significant negative correlation was also observed for the digit-forward condition ($\tau = -.065$, $p = .007$) and the square-backward condition ($\tau = -.079$, $p =.005$). However, there was no correlation between trial accuracy and probability of fixating the memory interest area in the square-forward condition ($\tau = -.024$, $p = .056$).

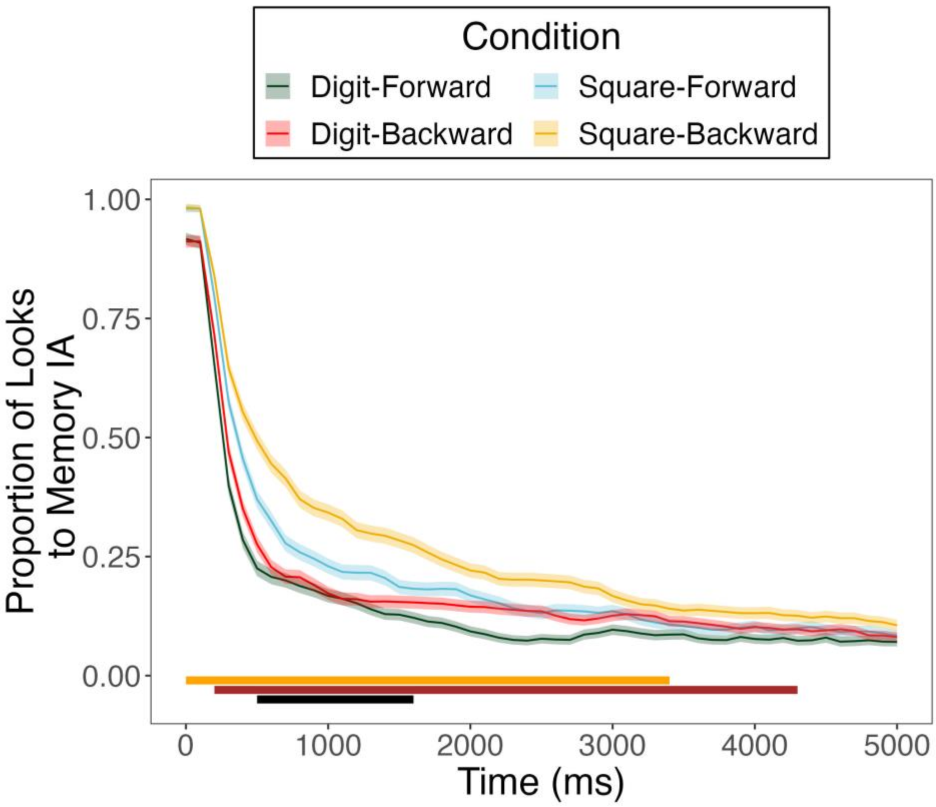

Figure 4.6 Time course of the proportion of looks to the memory interest area across conditions (digit-forward, digit-backward, square-forward, square-backward). Note that the retro cue is displayed from 0ms to 500ms. Horizonal lines at the bottom (y = -.01; -.15; ; -.20) denote significant cluster differences: orange illustrates the difference between the digit and square recall conditions; brown illustrates the difference between forward and backward recall conditions; black shows their interaction. Shaded areas represent within-participant standard errors around the mean calculated with the Cousineau-Morey method.

4.2.2.7 Was the action interest area looked at during retention?

Proportion of looks to the action interest area during the retention interval is illustrated in Figure 4.7 as a function of condition. For a supplementary graph illustrating the proportion of looks outside of the memory and action interest areas, please refer to Figure 3 in the Appendix.

A cluster-based permutation test was run based on a LMM with proportion of looks to the action interest area as a predictor and with recall condition (digit, square) and order condition (forward, backward) as fixed effects, their interaction, and random intercepts and slopes for these effects across participants. The cluster-based permutation tests revealed a difference between the digit and square conditions between 0-5000ms (cluster mass = 177.34, $p < .001$), and a significant difference between the forward and backward conditions between 500-2100ms (cluster mass = 266.46, $p < .001$).

A Kendall's tau correlation analysis was undertaken to explore the relationship between trial accuracy and average fixation probabilities to the action interest area. The analysis revealed that no correlation for the digit-backward condition ($\tau = .049$, $p = .415$). In contrast, a statistically significant weak positive correlation was observed for the digit-forward condition ($\tau = .108$, $p = .014$). Similarly, the square-backward condition showed a weak positive correlation ($\tau = .161$, $p < .001$), suggesting an increase in fixation probabilities. The square-forward condition also demonstrated a weak positive correlation ($\tau = .111$, $p = .017$).

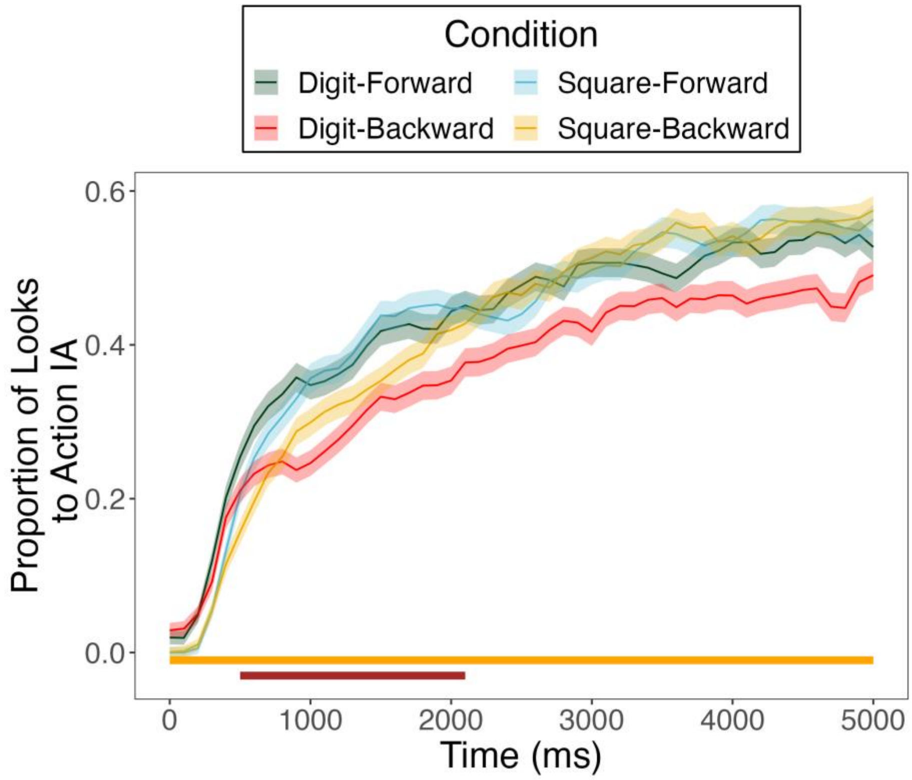

Figure 4.7 Time course of the proportion of looks to the action interest area across conditions (digit-forward, digit-backward, square-forward, square-backward). Horizonal lines at the bottom (y = -.01; -.15; -.20) denote significant cluster differences: orange illustrates the difference between the digit and square recall conditions; brown illustrates the difference between forward and backward recall conditions; black shows their interaction. Shaded areas represent within-participant standard errors around the mean calculated with the Cousineau-Morey method.

4.2.3 Discussion

Experiment 1 aimed to explore gaze during the encoding and maintenance of a list of items, either digits or locations of squares, and found unique gaze patterns associated with the type of information and the order direction. A higher recall accuracy in digit compared to square conditions was found. While higher recall accuracy was found for the digit-forward compared to digit-backward conditions, no evidence was found for a significant difference between the square-forward and square-backward conditions. These findings are in line with previous research suggesting that while recalling in backward order negatively impacts verbal but not spatial recall (e.g. Donolato et al., 2017). While the process underlying backward recall is still largely unclear (Lewandowsky & Farrell, 2008), important insight from eye movement measures are provided in the current study.

Overall, different oculomotor activity was found to differ across recall conditions, with higher mean saccade amplitude values for digit compared to square conditions. Findings revealed different encoding strategies for the square and digit recall, with higher probability of looks to presented items in the square recall conditions. A higher proportion of cumulative looks was also found, where the probability of looking to previous items was added to the probability of looking at each presented item, in the square compared to digit conditions. Overall, these findings are in line with previous research observing lower probability of looking at presented items in spatial compared to verbal tasks (Czoschke et al., 2019; Lange & Engbert, 2013; Patt et al., 2014)). These results suggest that while for verbal information participants precisely look at each presented digit to be able to distinguish its identity, for spatial information participants can employ a more global approach of encoding the locations, with a steady decrease of proportion of looks to each presented item from the list. Taken together with the lower saccade amplitude in the square compared to digit conditions, it might be that there is a lower cost of using eye movements in verbal encoding, while in spatial encoding saccadic suppression might be a strategy to reduce interference. Indeed, this would be in line with previous findings indicating that eye movements interfere with spatial working memory (Lawrence et al., 2004; Pearson & Sahraie, 2003).

Previous research has suggested that phonological encoding is preferred when preparing for a forward recall and visuospatial encoding for backward recall. For example, Guitard et al. (2020) found that manual-spatial tapping, which is shown to impair spatial representations, impaired backward but not forward digit recall. A difference in the proportion of looks to presented items between forward and backward order in digit recall was not found, with this finding failing to provide support for the employment of different encoding strategies depending on order direction for verbal information. Interestingly, for square recall significantly higher values were observed in the backward compared to forward order. This finding supports the view for different encoding strategies based on the direction of recall for spatial information and suggests that more precise looks are needed in backward order conditions. This could be that backward recall poses as a task with an increased difficulty which necessitates more looks to on-screen letters. Further, there were no differences in cumulative looks, between the forward and backward order for both the digit and square recall conditions. These findings suggest that further investigating how type of information to be recalled could influence encoding strategies might provide important insight about backward recall. It could also be that eye movement measures are less informative of potential employed strategies for verbal compared to visuospatial information. No significant correlations were found except for a negative relationship between the probability of looks to on-screen items and trial accuracy the square-forward condition. Considering cumulative looks, only a weak negative correlation was found between them and trial accuracy in the digit-forward condition. Taken together, no clear link was found between trial accuracy and looks during the encoding period.

Similarly to the encoding period, in the retention period an overall lower saccade amplitude was observed in the square compared to digit conditions, suggesting lower oculomotor activity when maintaining spatial information. An investigation of the proportion of looks to the memory (i.e. where the list of items was presented) and action interest areas (i.e. where participants had to recall items) during retention revealed higher values to both interest areas for the square compared to the digit conditions. While the proportion of looks to the memory interest area were higher for forward order in both the square and digit recall conditions, the opposite pattern was observed for the action interest area, with higher proportion of looks in the backward compared to forward order conditions. However, the difference between the proportion of looks to the action interest area between the backward and forward conditions were less clear, with the significant cluster being only observed in the first half of the period. Taken together, these findings suggest that while there was overall less oculomotor activity in the square recall conditions during retention, these looks were more strategically and efficiently utilised. Increased looks to the location of memorised items have been found for spatial compared to verbal information (e.g. Czoschke et al., 2019). The current study replicated these findings. This looking behaviour could be due to the increased difficulty associated with the square recall conditions and could be indicative of rehearsal attempts. Indeed, this account would explain the high proportion of looks to the memory interest area and the delayed disengagement to the memory interest area was observed in the square-backward compared square-forward condition.

Except for the square-forward condition, weak negative correlations were found between trial accuracy and proportion of looks to the memory interest area in all other conditions. Contrary to previous research finding positive correlations between accuracy and looks to memorised locations (e.g. Czoschke et al., 2019), the current data suggest that looks to the memory interest area, either due to lingering on or revisiting the area, might be due to participants struggling to maintain the memory list. However, Experiment 2 attempted to separate the lingering from revisits of the memory interest area for a clearer interpretation. Weak positive correlations were found between trial accuracy and looks to the action area for all conditions except for the digit-forward condition. This could be reflective of the memory list being successfully prepared, allowing the move to the planning and executing the relevant actions (which requires looking at the action interest area) for recall.

4.3 Experiment 2

In Experiment 2, the paradigm used in Experiment 1 was modified to allow clearer interpretation of eye movement data. Specifically, retro cues were included for two purposes: firstly, it allowed a more refined analyses of oculomotor activity by reducing the number of relevant items by providing one location to be identified as the area of interest, and secondly, it directed attention to the centre of the screen so that any looks to either the memory or action interest area would not be due to lingering to the encoding area where the memory list was presented. As mentioned in the previous chapter, retro cues enhance attention and recall by directing focus to specific representations after they are encoded, similar to how cues in the Posner paradigm direct attention. However, unlike the Posner paradigm (Posner, 1980), retro cues are presented post-encoding (for a review, see Souza & Oberauer, 2016). This mechanism is suggested to improve recall performance by enhancing the storage and accessibility of targeted memory items, showing the effectiveness of retro cues in guiding internal attention (Griffin & Nobre, 2003; Lepsien et al., 2005; Sligte et al., 2008).

4.3.1 Method

4.3.1.1 Participants

Twenty-four participants took part in the experiment. Two participants were excluded due to poor eye tracking calibration and validation values (the mean spatial accuracy was worse than 0.5 degree or a maximum spatial accuracy worse than 1 degree for each performed validation procedure). The 22 remaining participants (3 male) ranged from 18 to 31 (M = 20.64; SD = 3.1). All participants were students at Cardiff University and were recruited via the School of Psychology's participant panel, social media and word of mouth. All had normal or corrected-to-normal vision. Sample size was not predetermined using statistical methods; instead, it was selected to align with sample sizes used in similar previous studies, which typically included 20 to 30 participants (Czoschke et al., 2019; van Ede et al., 2019).

4.3.1.2 Apparatus and Materials

The same apparatus and materials were used as in Experiment 1.

4.3.1.3 Design

The combinations of the task type (square or digit recall), side of presentation area and recall area of the display (left and right side of the screen, or right and left side of the screen), and cue order direction (forward or backward) were blocked (eight blocks in total) and randomised across participants. All participants took part in all conditions within a single session.

4.3.1.4 Procedure

The encoding phase was identical to that of Experiment 1. A blank screen for retention was then presented for 1000ms. The cue and recall sequence then began. This was followed by a centrally presented serial position cue which prompted forward or backward recall (e.g. 1^{st}, 3^{rd}, 7^{th} or 6^{th},4^{th},2^{nd}) presented for 500ms and with a 2000ms blank screen. The recall screen was then presented, showing either the square grid for the block recall task or the digits (0-9) in two rows (see Figure 4.8d) for up to 3000ms. Upon a mouse click, a blank screen was presented for the remaining time of those 3000ms, which was then followed by a 250ms blank screen. Next, this cue and recall sequence was repeated two more times.

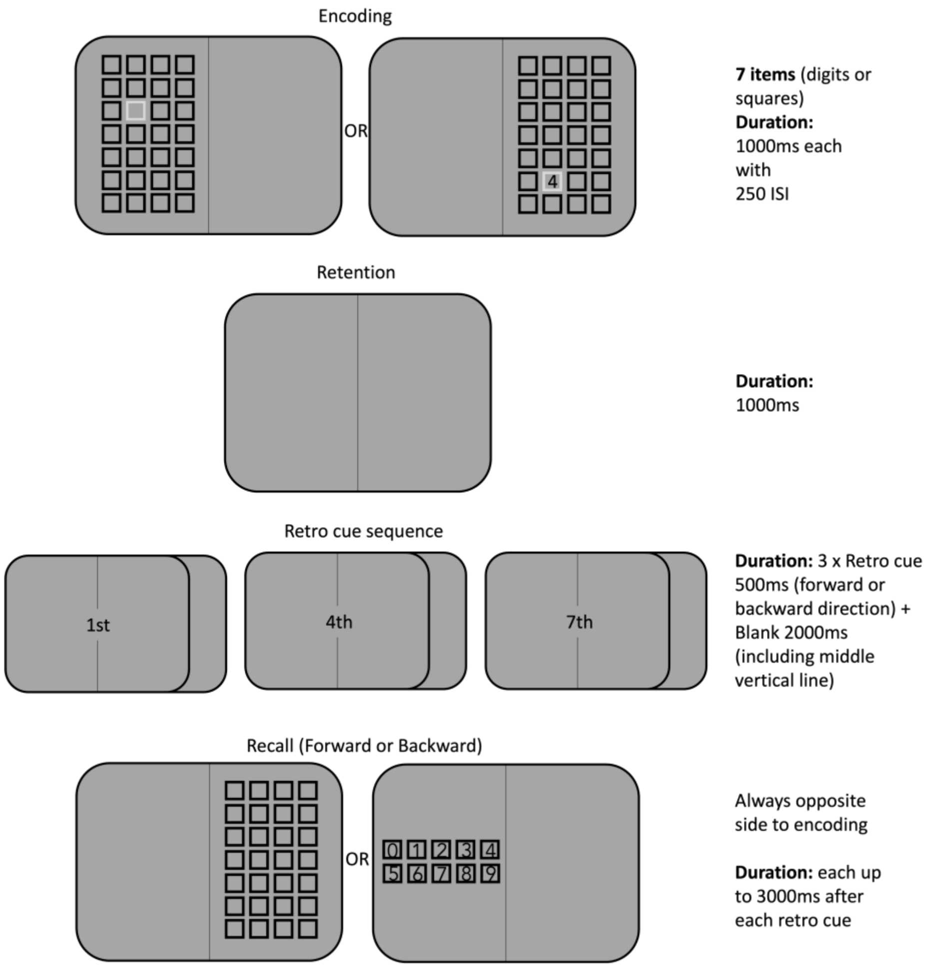

Figure 4.8 Trial sequence of Experiment 2 showing examples of encoding, retention, retro cue sequence, and recall displays. The cues refer to the sequential order of the previously presented items.

4.3.2 Results

4.3.2.1 Data Analysis

The data analysis plan was identical to the one for Experiment 1.

4.3.2.2 Recall Accuracy

In order to consider the influence of recall and order conditions on recall accuracy (Figure 4.9), a LMM was run which included trial accuracy as a dependent variable and recall condition (digit, which was contrast coded as 1, and square, which was contrast coded for -1) and order condition (backward, which was contrast coded as 1, and forward, which was contrast coded for -1) as categorical fixed factors. Participant was included as a random factor with random intercepts and slopes. The model revealed a significant effect of recall condition (b = .318, SE = .029, t = 11.16, p < .001), with trial recall accuracy significantly higher in the digit conditions (M = .65, SD = .35) compared to square conditions (M = .23, SD = .25). The model also revealed a non-significant effect of order condition (b = .012, SE = .012, t = 1.06, p = .30). The interaction between the recall and order conditions was significant (b = -.042, SE = .009, t = -4.44, p < .001).

To further investigate this interaction, the digit and square conditions were considered separately. In the square conditions, there was a significant difference between trial accuracy in forward and backward order conditions (b = .05, SE = .013, t = 14.87, p < .001), with significantly higher values in the backward order condition (M= .26, SD = .25). In the digit recall conditions, there was no significant difference found between the forward and backward order conditions (b = -.029, SE = .017, t = -1.74, p = .10). For a graph showing a lenient scoring of the square conditions, please refer to Figure 4 in the Appendix.

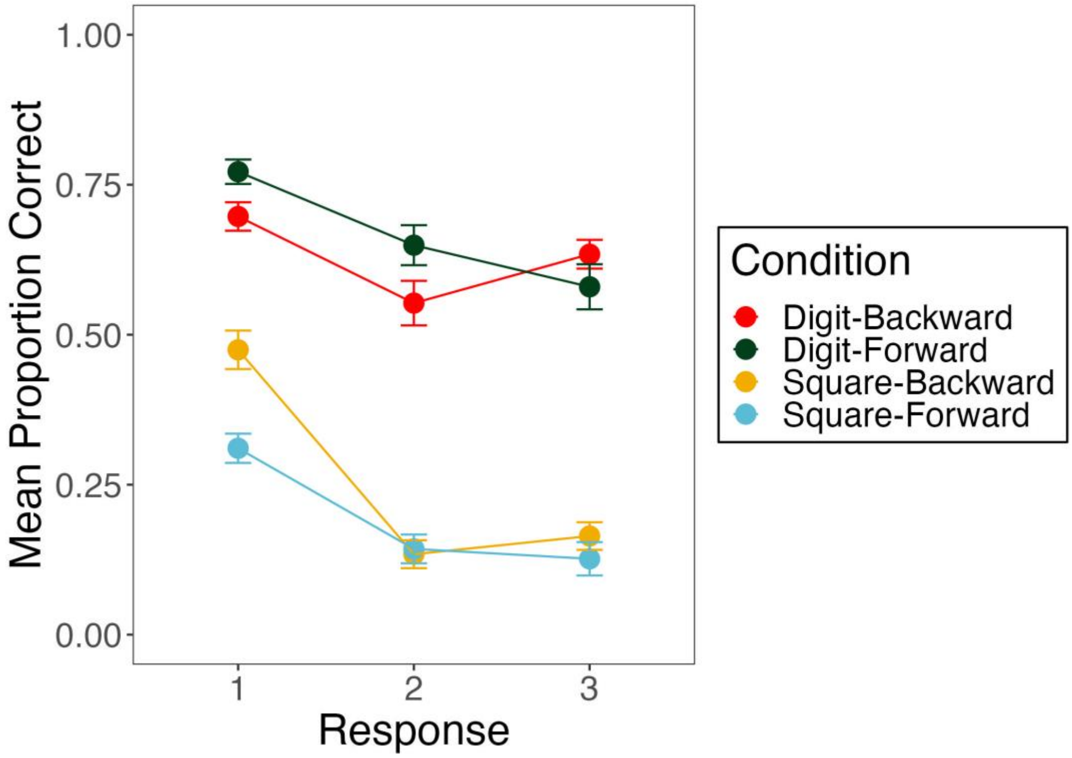

Figure 4.9 Mean proportion correct as a function of condition (central, novel-changing, typical) and response position (1-3). Error bars mark within-participant standard errors around the mean calculated with the Cousineau-Morey method.

4.3.2.3 How much oculomotor activity occurred during the encoding and retro cue periods?

A LMM model was run to evaluate the effects of recall condition and order condition on saccade amplitude during the encoding period (Figure 4.10). Random effects included random intercepts and slopes, and their interaction. The model revealed a significant effect of recall condition ($b = .015$, $SE = .005$, $t = 3.23$, $p = .004$), with higher saccade amplitude in the digit condition ($M = 4.96$, $SD = 1.07$) compared to the square recall condition ($M = 4.64$, $SD = 1.35$). There was no significant effect of order condition ($t = .15$, $p = .89$), or the interaction between recall and order conditions ($t = .72$, $p = .48$).

A model was run with saccade amplitude as a dependent variable and with recall condition and order condition as fixed effects during the retro cue periods. The random effects structure included random intercepts and slopes, and their interaction. Recall condition significantly predicted saccade amplitude, with digit tasks (M = 4.88, SD = 1.98) associated with a slight decrease compared to square tasks (M = 5.23, SD = 1.75), with b = -.015, SE = .005, t = -3.07, p = .006. There was no significant effect of order condition (t = -.037, p = .971). The interaction between recall condition and order condition also did not significantly predict saccade amplitude (t = -.702, p = .491).

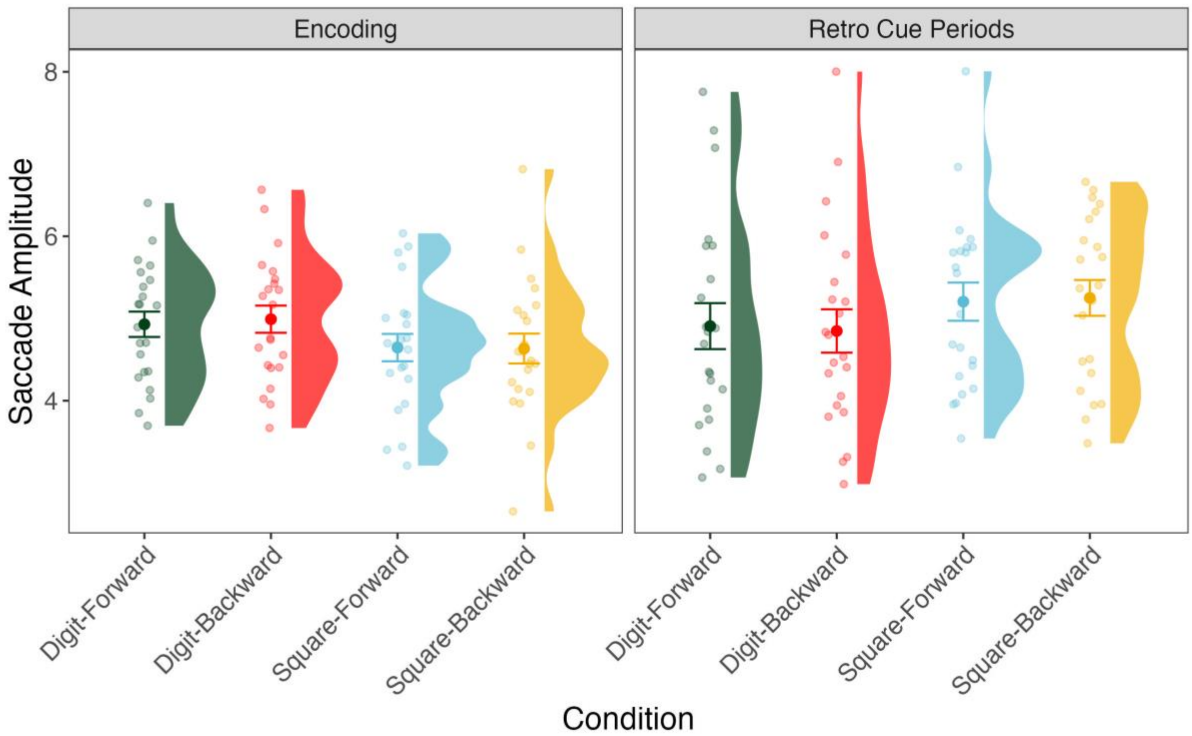

Figure 4.10 Mean saccade amplitude in visual degrees for each condition during the encoding and retention periods. Error bars show one standard error around the overall mean per condition. Points represent participant-specific means. Density curves along the continuous axis reveal data distribution and density across conditions.

4.3.2.4 What was looked at during encoding?

To investigate the effects of recall and order conditions on the likelihood of fixating on displayed items (Figure 4.11), a Linear Mixed Model (LMM) was employed. The dependent variable in this model was trial accuracy, while recall condition (with digit represented by 1, and square by -1) and order condition (with backward represented by 1, and forward by -1) were included as categorical fixed factors. Furthermore, the model incorporated random slopes for task type for individual participants.

The model resulted in a significant effect of recall condition (b = .030, SE = .003, t = -9.95, p < .001), with fixation probability to the presented item significantly higher in the digit conditions (M = .48, SD = .09) compared to square conditions (M = .32, SD = .13). The model revealed a non-significant effect of order condition (t = -.46, p = .65). The interaction between the recall and order conditions was significant (b = .001, SE = .001, t = 2.02, p = .04).

To further investigate this interaction, separate models were run for the square and digit recall conditions. In the square recall conditions, there was no significant difference between forward and backward order condition (t = -1.14, p = .27). There was also no significant difference in the digit recall conditions between forward and backward order (t = 1.09, p = .29). This suggests that while the interaction in fixation proportion appears significant, its practical impact is minimal, as indicated by the lack of significant differences in simple effects analysis between order types for both digits and squares.

A Kendall's tau correlation analysis was conducted to explore the association between average fixation probabilities to presented items across conditions. The analysis revealed that there was no statistically significant correlation in the digit-forward condition, τ = -0.046, p = .288. Similarly, no correlation was found in the square-forward condition, τ = -0.076, p =

.058, and the square-backward condition, τ = 0.014, p = .701. Conversely, a significant negative correlation was observed in the digit-backward condition, τ = -0.163, p < .001.

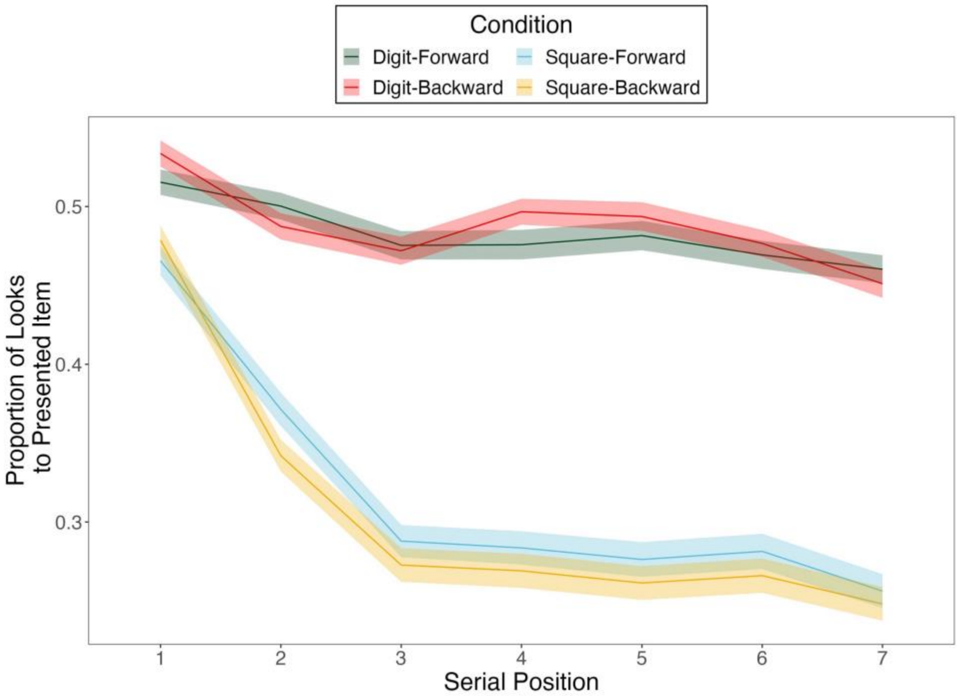

Figure 4.11 Mean fixation proportion of each of the on-screen items for each condition. Shaded areas represent within-participant standard errors around the mean calculated with the Cousineau-Morey method.

4.3.2.5 Did cumulative looks differ across conditions?

To investigate the effects of recall and order conditions on the cumulative probability of fixating the presented and previously presented items (Figure 4.12), a Linear Mixed Model (LMM) was run. The dependent variable in this model was cumulative fixation probability, while recall condition and order condition were included as categorical fixed factors. Furthermore, the model incorporated random intercepts and slopes. The model revealed a main effect of recall condition (b = .002, SE = .0003, t = 4.76, p < .001), with higher cumulative fixation probability in the digit (M = .58, SD = .11) compared to the square recall condition (M = .49, SD = .16). There was no significant effect of order condition (t = .37, p = .71). The interaction effect was significant (b = .0002, SE = .0001, t = 2.71, p = .007).

To investigate this interaction, two follow-up models were conducted to look at digit and square conditions separately. There was no significant effect of order condition in the square order condition (t= -1.42, p = .16). However, in the digit conditions, the cumulative fixation proportion was higher in the backward compared to forward order, with (b = .0003, SE = .0001, t = 2.57, p = .01).

A Kendall's tau correlation analysis conducted to assess the relationship between trial accuracy and in cumulative fixation probabilities across recall condition (digit, square) and order condition (backward, forward) revealed a weak negative correlation for the digit-backward condition (τ = −.152, p < .001) and a weak negative correlation for the digit-forward condition (τ = −.119, p = .012). However, no correlations were found between trial accuracy and cumulative looking behaviour in the square-backward condition (τ = .029, p=.39) and the square-forward condition (τ = .039, p = .56). These findings suggest cumulative fixation probabilities in digit conditions, irrespective of order condition, are associated with a decrease in trial accuracy.

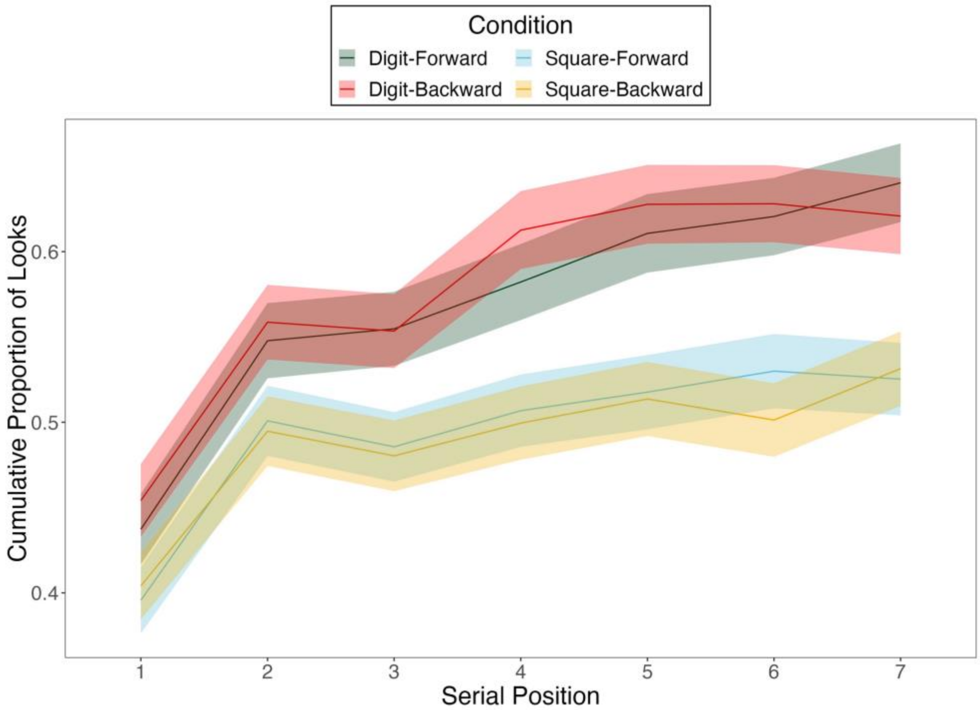

Figure 4.12 Mean proportion of samples to cumulative item locations as a function serial position (1-7) across each condition (digit-forward, digit-backward, square-forward, square-backward). Error bars mark within-participant standard errors around the mean calculated with the Cousineau-Morey method.

4.3.2.6 Was the memory interest area looked at during retention?

Proportion of looks to the memory interest area during each of the three retro cue periods (consisting of the 500ms retro cue presentation display and a blank 2000ms display) is illustrated in Figure 4.13 as a function of condition.

A cluster-based permutation test was run based on a LMM with proportion of fixating the relevant cued item interest area as a predictor and with recall condition (digit, square) and order condition (forward, backward) as fixed effects, their interaction, and random intercepts and slopes for these effects across participants. The cluster-based permutation tests revealed a difference between the digit and square conditions: in the first retro cue period between 0-2500ms (cluster mass = 1308.57, $p < .001$), in the second retro cue period between 700-

2500ms (cluster mass = 254.31, $p < .001$), and in the third retro cue period between 1500-2500ms (cluster mass = 109.55, $p < .001$). No significant differences between forward and backward conditions were found, with no significant clusters identified.

A Kendall's tau correlation analysis was undertaken to explore the relationship between trial accuracy and average fixation probabilities to the memory interest area across conditions. The results showed a weak negative correlation for the digit-forward condition, $\tau = -0.035$, $p = .026$, and the digit-backward condition, $\tau = -0.042$, $p = .015$. However, no statistically significant correlation was observed for the square-forward condition, $\tau = 0.051$, $p = .232$, and the square-backward condition, $\tau = 0.029$, $p = .448$, indicating that fixation probability patterns in these conditions did not significantly interact with trial accuracy.

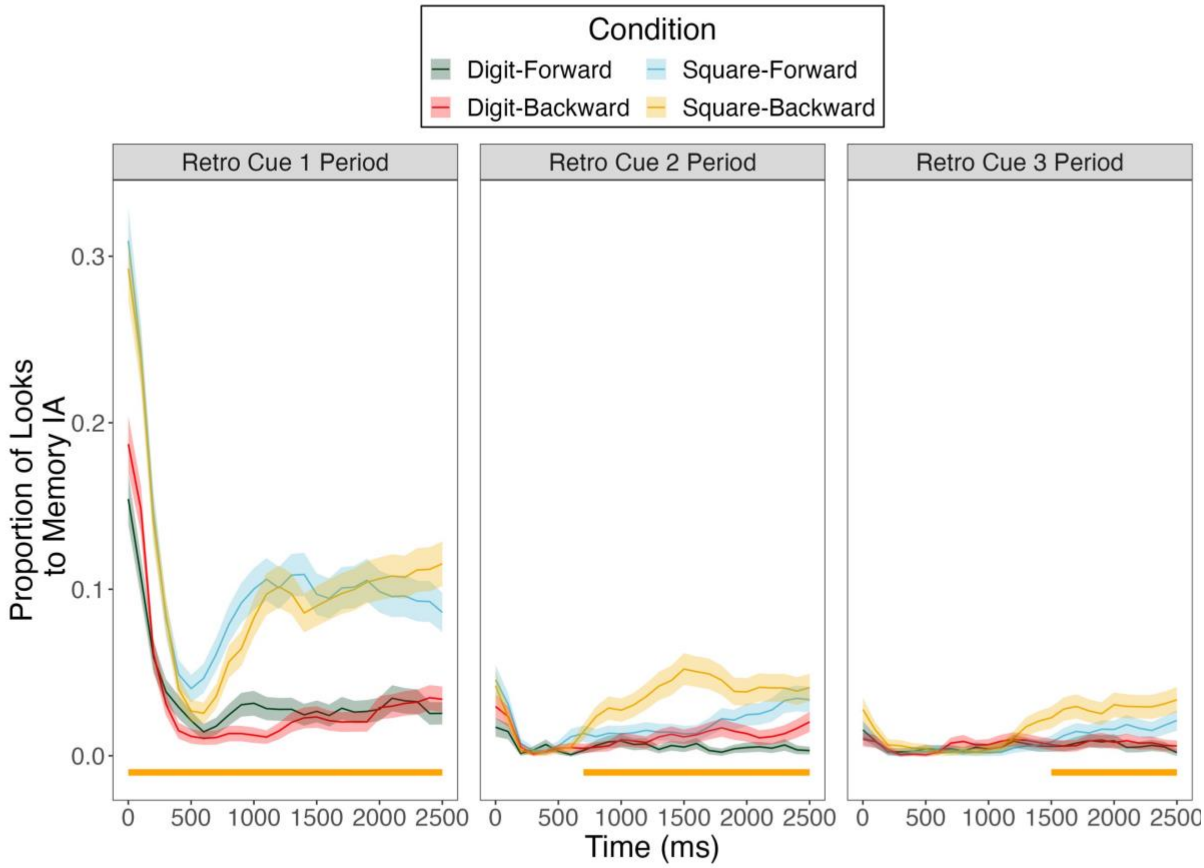

Figure 4.13 Time course of the proportion of looks to the memory interest area across conditions (digit-forward, digit-backward, square-forward, square-backward). Note that the retro cue is displayed from 0ms to 500ms. Horizonal lines at the bottom (y = -.01; -.15; -.20)

denote significant cluster differences: orange illustrates the difference between the digit and square recall conditions; brown illustrates the difference between forward and backward recall conditions; black shows their interaction. Shaded areas represent within-participant standard errors around the mean calculated with the Cousineau-Morey method.

4.3.2.7 Was the action interest area looked at during retention?

Proportion of looks to relevant cued item during each of the three retro cue periods (consisting of the 500ms retro cue presentation display and a blank 2000ms display) is illustrated in Figure 4.14 as a function of condition. For a supplementary graph illustrating the proportion of looks outside of the memory and action interest areas, please refer to Figure 5 in the Appendix.

A cluster-based permutation test was run based on a LMM with proportion of fixating the relevant cued item interest area as a predictor and with recall condition (digit, square) and order condition (forward, backward) as fixed effects, their interaction, and random intercepts and slopes for these effects across participants. The cluster-based permutation tests revealed a difference between the digit and square conditions: in the first retro cue period between 500-1800ms (cluster mass = 472.88, $p < .001$), in the second retro cue period between 400-2500ms (cluster mass = 1528.63, $p < .001$), and in the third retro cue period between 400-1900ms (cluster mass = 418.84, $p < .001$). There was also a significant difference between the forward and backward conditions in the second retro cue period between 500-2500ms (cluster mass = 202.22, $p < .001$)

A Kendall's tau correlation analysis was used to explore the relationship between trial accuracy and average fixation probabilities to the action interest area across conditions. The analysis revealed statistically significant weak positive correlations for the digit-backward condition, $\tau = 0.122$, $p = .010$, and the digit-forward condition, $\tau = 0.123$, $p = .007$, indicating an increase in fixation probabilities in these scenarios. However, no statistically significant correlation was observed for the square-forward condition, $\tau = 0.021$, $p = .598$, and the square-backward condition, $\tau = 0.036$, $p = .430$.

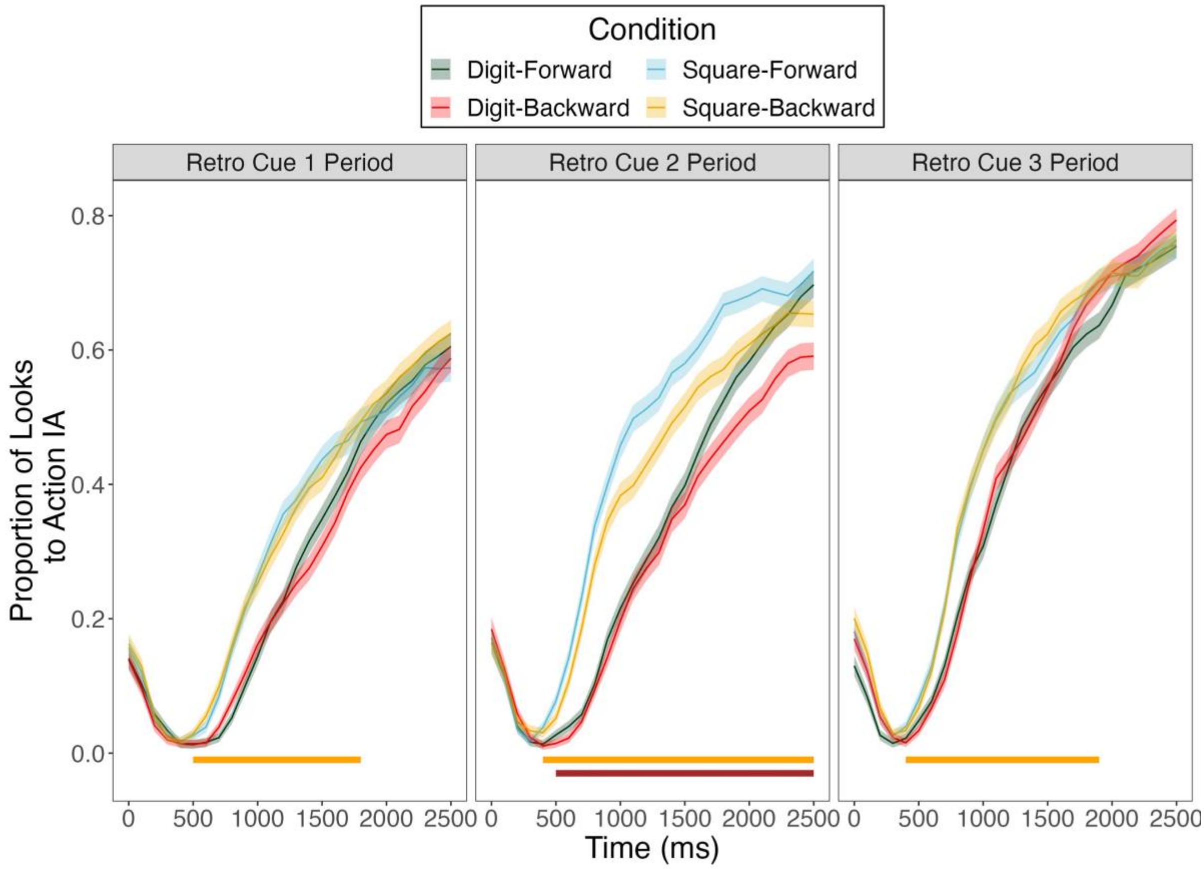

Figure 4.14 Time course of the proportion of looks to the action interest area across conditions (digit-forward, digit-backward, square-forward, square-backward). Note that the retro cue is displayed from 0ms to 500ms. Horizonal lines at the bottom (y = -.01; -.15; -.20) denote significant cluster differences: orange illustrates the difference between the digit and square recall conditions; brown illustrates the difference between forward and backward recall conditions; black shows their interaction. Shaded areas represent within-participant standard errors around the mean calculated with the Cousineau-Morey method.

4.3.3 Discussion

Experiment 2 replicated the findings of Experiment 1 of higher recall accuracy in digit compared to square conditions. However, in contrast to Experiment 1, there was a difference between forward and backward order conditions in square but not in digit recall. This contrasts with previous findings suggesting that recalling in backward order negatively impacts verbal but not spatial performance (e.g. Donolato et al., 2017). Retro cues, which were incorporated in the design of Experiment 2, are suggested to enhance the storage and accessibility of the target item, resulting in higher recall performance compared to conditions where attention is distributed equally across all items (Griffin & Nobre, 2003; Lepsien et al., 2005; Sligte et al., 2008). While this suggests that retro cued recall should be enhanced compared to list recall, specifically for visual information (Morey et al., 2013), it could be that that the observed differences are due to the introduced delay by the retro cue periods.

Consistent with Experiment 1, Experiment 2 found higher saccade amplitudes during encoding in digit compared to square conditions, indicating more extensive oculomotor activity when recalling verbal information. The absence of significant effects for order condition or its interaction with recall condition across both experiments suggests a stable pattern of oculomotor engagement irrespective of presentation order. Similar to Experiment 1, during encoding a higher proportion of looks were directed to on-screen items in the digit compared to square conditions. Further, a higher proportion of cumulative looks was observed in the digit compared to the square recall conditions. However, no differences were found between forward and backward order conditions both in the square and digit recall conditions for both proportion of looks to presented items and cumulative looks. These findings provide support for previous research showing a decrease in looks to on-screen items in spatial compared to verbal tasks (Czoschke et al., 2019; Lange & Engbert, 2013; Patt et al., 2014). However, the lack of a difference between forward and backward order in looks to presented items in Experiment 2 do not suggest that different encoding strategies were used for backward compared to forward order. Further, the only significant correlation found was a negative correlation between trial accuracy and proportion of looks to presented items in the digit-backward condition. A weak negative correlation was also found between cumulative looks and trial accuracy in both the digit-backward and digit-forward conditions. While these correlations do not provide a clear link between looking behaviour and accuracy, these may be an indication that participants are more likely to look to the presented and previous items when they are struggling to remember items.

During the retro cue periods, a higher likelihood of looking to memory and action interest areas was found in the square compared to digit conditions. A higher probability of looks to the memory interest area was also found in the forward compared to backward order, but this was only observed in the second retro cue period. As at the beginning of each retro cue period a retro cue was presented in the centre of the screen, directing participants' attention away from the memory area. Indeed, a relatively low probability of fixating the memory area was found compared to Experiment 1. This suggests that while participants rarely visited the memory area, they were more likely to fixate it when recalling spatial compared to verbal information. These findings are in line with the view that eye movements are influenced by both memory and action relevant locations (e.g. van Ede, 2020, for a review), specifically for spatial information. Additionally, while a weak negative correlation was found between trial accuracy and proportion of looks to the memory interest area for the digit-forward and the digit-backward condition, weak positive correlations were found between trial accuracy and proportion of looks to the action interest area for the digit-forward and the digit-backward condition. However, no clear indication of successful rehearsal resulting in enhanced performance was found, which would be indicated as a positive correlation between trial accuracy and looks to the memory area. Instead, negative correlations were found which might suggest that participants are more likely to look back to memorised locations when they are having difficulty recalling them, reflecting a rehearsal attempt. The exploration of gaze allocation to memory and action interest areas during retention periods offered novel insights in Experiment 2. While significant differences were observed between digit and square conditions across all retro cue periods, the forward and backward conditions exhibited nuanced differences, especially in the action interest area. These findings suggest that the strategy of gaze allocation during retention may vary significantly depending on the recall and order conditions, potentially reflecting different cognitive strategies or processing demands.

4.4 General Discussion

Across two experiments, data show clear evidence for differences in the looking behaviour to memory- and action-relevant areas when recalling verbal or spatial information during both encoding and maintenance phases.

A consistent theme across both experiments was the superior recall accuracy observed in digit conditions compared to square conditions, which is consistent with previous findings (e.g. Morey et al., 2013). Interestingly, while Experiment 1 highlighted a general advantage for forward order conditions, Experiment 2 revealed that order effects might be contingent upon the type of material being recalled, as evidenced by the significant improvement in backward order condition for square recalls.

In both experiments it was consistently found that on-screen proportion of looks were higher in the verbal compared to spatial conditions, replicating previous findings (Czoschke et al., 2019; Lange & Engbert, 2013; Patt et al., 2014). However, a higher proportion of cumulative looks during encoding was not found in the spatial compared to verbal conditions (Czoschke et al., 2019), and instead the current data revealed the opposite pattern of higher values in the digit conditions. This could be due to the specific task design where the memory- and action-relevant locations are separate.

During the retention period and retro cue periods, the memory interest area was much more likely to be looked at in Experiment 1, perhaps due to a delayed disengagement from these locations of the presented memory items. Indeed, in Experiment 2 the introduction of retro cues after the presentation of the memory items directed attention away from the memory interest area which resulted in much lower proportion of looks to the memory area. In both experiments, a higher proportion of looks to the memory interest area was found in square compared to digit recall. The proportion of looks to the action-relevant area was relatively high in both experiments towards the end of the relevant interest period. These findings are consistent with the view that working memory and eye movements can be biased towards both memorised and action-relevant locations (e.g. van Ede, 2020). They highlight the strategic allocation of visual attention based on task demands and the nature of the information being recalled. These patterns suggest that participants may engage different cognitive and visual strategies during the retention interval, possibly to enhance recall or to mitigate interference.

In Experiment 1, a higher proportion of looks to the memory interest area was found in backward compared to forward order and the opposite pattern for proportion of looks to the action interest area, with higher values observed in forward compared to backward order. However, in Experiment 2, a higher proportion of looks was found to the action area for forward compared to backward recall only in the second retro cue period. The current findings add to the literature on backward order (e.g. Donolato et al., 2017; Guitard et al., 2021, 2022) by tracking gaze shifts which revealed that the type of information to be recalled emerges to have an influence on these patterns. Future research should further investigate how eye movements can provide insights about the processes underlying backward recall.

Overall, weak negative correlations were found between trial accuracy and looks to memorised locations which might be an indication of an attempt to rehearse information with which participants are struggling rather than a clear indication of looking back boosting performance. Positive correlations were also observed with proportion of looks to the action interest area, suggesting that participants are likely to look at the action area when they have successfully prepared the memory list for recall. While in Experiment 1 eye movements to the action interest area in all conditions except for the digit-backward were found to have a weak positive relationship with trial accuracy, in Experiment 2 there was a weak positive correlation between the gaze pattern and trial accuracy in the digit conditions. While there was no consistent pattern for these, the inclusion of the retro cue procedure where a central retro cue is presented post-encoding of the items is influencing the looking pattern. While it could also be that probing 3 out of the 7 items in Experiment 2 in comparison to the list recall in Experiment 2 contributes to these different patterns in correlations with trial accuracy, performance between the two tasks was similar. Despite these differences, the positive correlations are in line with the idea that working memory is biased towards action-relevant information and that it has an important function in facilitating goal-directed actions (for a review, see Heuer et al., 2020).

The findings from these experiments contribute to a deeper understanding of the cognitive and visual processes underpinning memory recall tasks. They underscore the importance of considering both the nature of the material and the order of recall when investigating memory performance. Furthermore, the observed patterns of eye movements offer valuable insights into the strategies employed by individuals during memory encoding and retention. These insights have broad implications for theories of memory and cognition, suggesting that future research should continue to explore the dynamic interactions between visual attention, cognitive strategies, and memory performance.

5 General Discussion

The link between eye movements and working memory has been extensively researched (for reviews, see Heuer et al., 2020; van Ede, 2020). However, it is less clear how and why we use our eyes when maintaining spatial and verbal memory representations. This thesis explored the mechanisms and role behind the use of eye movements during the encoding and maintenance of information, as well as factors that may influence these oculomotor patterns. Throughout this thesis, potential differences in gaze shifts associated with processing spatial versus verbal information were investigated, along with any variations in eye movements that emerge from recalling information in different recall order.

5.1 Summary of Findings

Chapter 2 replicated previous findings of a difference in the use of eye movement patterns during encoding between verbal and spatial materials. The study built upon previous work by examining gaze shifts during both memory encoding and maintenance periods and the influence of foreknowledge of recall order on these patterns. This was achieved by asking participants to recall items either in forward or shuffled order, which was informed by retro cues referring to the sequential order of previously presented items. During the maintenance period, an increase in gaze shifts towards previously presented relevant items was observed for spatial materials when the recall order was unpredictable, compared to periods when it was predictable.

In *Chapter 3*, two experiments examined gaze shifts in a visuospatial bootstrapping task, which is suggested to involve the use of long-term memory. The paradigm which involved encoding verbal information in a familiar or novel spatial layout, was used to investigate potential differences in eye movement patterns when long-term memory spatial representations could be used to boost performance. We found unique gaze shift patterns, indicative of the use of different strategies during memory encoding and maintenance depending on the presence of long-term spatial information. Most notably, during the maintenance period it was found that gaze was focused on items towards the end of the memory list when verbal information was presented in a spatial array, with familiar and novel layouts eliciting unique oculomotor patterns. These findings provide evidence for the use of long-term memory representations significantly influencing gaze shifts.

Chapter 4 involved a novel task separating the locations where items were presented and recalled and aimed to investigate biases associated with output preparation or memory rehearsal. It was found that gaze is biased towards locations that previously contained relevant items more often when recalling spatial compared to verbal materials. Gaze differences to action-relevant locations were observed for spatial and verbal information, with higher probability of looks to the action area observed for spatial materials. These findings suggest that during the maintenance period attention is biased both towards memorised and action-relevant locations.

Overall, in all chapters limited evidence for eye movements having a functional role in facilitating performance was found, and instead the data suggest that the observed gaze shifts can be indicative of rehearsal attempts. Results also showed that during the encoding of verbal information, there was a consistently high likelihood of participants directing their gaze towards presented items throughout the memory list. In contrast, when encoding spatial information, there was a notable and steady decline in this tendency. These findings suggest that different gaze patterns are used when encoding different types of information.

5.2 Significance

The main contribution of this thesis lies in charting gaze activity while maintaining spatial and verbal information and in identifying potential moderating factors. Findings show a greater strategic involvement of eye movements when maintaining spatial information. This is consistent with the idea that oculomotor activity and spatial working memory have a tight link (e.g. Heuer et al., 2020; Morey, 2018; Olivers & Roelfsema, 2020; Stigchel & Hollingworth, 2018; Tremblay et al., 2006).

Findings from *Chapter 2* suggest that different oculomotor strategies are used during memory maintenance when recall order is predictable and when it is unpredictable, identifying foreknowledge as a factor moderating gaze shifts. *Chapter 3* (Experiment 2) and *Chapter 4* (Experiment 1 and 2) included backward recall, and revealed gaze differences, but these were not consistent and warrant further research. As past research suggests greater reliance on visuospatial representations of backward recall (Guitard et al., 2020; Miles et al., 1991; Watkins et al., 2000), future investigations may benefit from recording and analysing eye movements during various backward order tasks to provide additional insights into the processes and strategies behind backward recall order.

Findings from *Chapter 3* suggest that using long-term memory representations elicit unique gaze patterns, suggesting a unique strategic use of maintaining information in familiar spatial layout. These findings are consistent with previous research showing different patterns of eye movements associated with expertise in various tasks, such as in chess games (e.g. Reingold & Charness, 2005) and in exploring CT scans (for a review, see Van Der Gijp et al., 2017). Further, findings from *Chapter 3* are consistent with the assumption that domain-specific resources can be used together to boost immediate memory but provided limited support for the notion that the oculomotor system facilitates sequential spatial rehearsal (e.g. Gonthier, 2021).

Chapter 4 distinguished between gaze biases to memorised locations and action-relevant locations, with findings consistent with the research suggesting that eye movements are not only for preparing for action, but they can also be directed to memorised spaces (e.g. van Ede, 2020; van Ede et al., 2019), perhaps indicating oculomotor rehearsal attempts. However, when attention was directed away from the memory location at the beginning of the retention period, low probability of spontaneous revisiting of memorised spaces was found.

The findings of this thesis that encoding verbal information is associated with more precise looks to presented items, while for spatial information there is a steady decrease in looks to presented items, replicate previous findings (Czoschke et al., 2019; Lange & Engbert, 2013; Patt et al., 2014) and extended this work by considering cumulative looks (*Chapters 3 and 4*). The data suggest that these gaze patterns reflect different encoding strategies.

The findings also have implications for working memory models. Baddeley et al. (2021) propose that a visuospatial component of the multiple-component working memory system should be viewed as more reliant on executive resources compared to the verbal component. The findings in this thesis largely align with this perspective, with consistent findings of gaze pattern differences between spatial and verbal information across encoding and maintenance periods. Indeed, this is further supported by consistent findings that visuospatial memory is hindered more by dual-task interference compared to verbal memory (e.g. Morey, 2018). While the findings from this thesis support the view that domain-specific resources can be utilised together to boost memory (*Chapter 3*), the lack of a clear link between gaze patterns and recall suggests that gaze can provide limited support for spatial rehearsal. The multicomponent model also assumes that domain-specific resources together can aid working memory. This thesis is in line with this view, but the lack of a clear link between gaze patterns and accuracy suggests that eye movements have only a limited role in rehearsal. Barrouillet & Camos (2021) identify two key maintenance mechanisms for verbal working memory: an articulatory process, which appears to rely on functions similar to those used in language production and is specific to verbal information, and a domain-general attentional process that aids in retaining both visuospatial and verbal information. This thesis is in line with this idea, as findings consistently have shown lower involvement of eye movements during the maintenance period for verbal compared to spatial information, despite higher performance for verbal memory. The significant limitations on the extent to which eye movements might support spatial memory suggest that additional support is often necessary for successful maintenance. Overall, these results align with the assumption that domain-specific resources can be integrated to enhance immediate memory, but they provide limited support for the idea that the oculomotor system facilitates robust and sustained serial spatial rehearsal.

Throughout this thesis, a variety of methodological tools were employed with the aim to enhance the robustness and clarity of the eye movement analyses. Among these, retro cueing, which consisted of digits referring to the serial position of presented items, was used to select only one item at a time during the maintenance interval. Retro cueing has been suggested to improve the storage and accessibility of the cued item (Souza & Oberauer, 2016). The findings from the current thesis suggest that the inclusion of retro cues should be considered in future studies focusing on eye movement analyses for a clearer investigation, as list recall might involve multiple strategies which are more difficult to discern.

In *Chapter 4*, the introduction of a novel paradigm facilitated the distinct separation between gaze biases attributable to output preparation and those stemming from the revisiting of memorized locations. This differentiation underscores the significance of meticulously considering the spatial relationship, whether overlapping or separate, between action-relevant and memory-relevant locations when investigating eye movements in the context of memory and cognitive tasks. The ability to isolate these biases is paramount, as it provides a clearer insight into the underlying cognitive mechanisms at play. Specifically, separating the locations pertinent to memory from those linked to action execution enables future investigations to more accurately identify whether the observed gaze shifts are a result of the participants preparing their responses (output preparation) or actively rehearsing the memorized information through oculomotor processes. This distinction is critical for understanding the cognitive strategies employed by individuals in managing and manipulating stored information for task execution. It also offers valuable implications for the role of eye movements in cognitive processes, suggesting that gaze patterns could serve dual functions: facilitating the cognitive rehearsal of spatial information and preparing for the physical enactment of responses. Moreover, this separation allows for a nuanced analysis of the extent to which oculomotor rehearsal contributes to memory retention and retrieval, as opposed to being primarily a byproduct of planning motor actions. By examining the conditions under which gaze biases towards memory-relevant locations increase or decrease, future investigations can infer the relative contributions of these two processes to task performance. This, in turn, enriches our understanding of the complex interactions between spatial memory, attentional allocation, and motor planning, providing a more comprehensive view of the cognitive architecture supporting these functions. Therefore, the paradigm introduced in *Chapter 4* not only demonstrates the importance of spatial configuration in eye movement research but also highlights the potential of such methodologies to dissect the multifaceted roles of gaze in cognitive processes. Through careful experimental design and analysis, it becomes possible to disentangle the intertwined aspects of cognitive rehearsal and motor preparation, paving the way for a deeper exploration of the mechanisms driving memory and action.

These methodological choices were critical in dissecting the complex interplay between attention, memory, and spatial cognition, providing valuable insights into the underlying mechanisms of working memory and should be considered for future investigations.

5.3 Future Directions

The current line of research aimed to systematically explore and map the potential differences in gaze when recalling spatial or verbal information and would hopefully inspire further investigations. This research had several important limitations to note. The sample sizes are not suited for detecting small effects and therefore future work should aim to provide bigger sample sizes to further investigate the link between gaze patterns and memory. This would also enable the exploration of individual differences in cognitive processing, particularly in the context of encoding and maintaining verbal versus spatial information, which opens promising avenues for future research. For example, obtaining the working memory span for individuals and taking those into account when investigating gaze and memory might provide additional insight into these processes. Specifically for tasks with a list size over 4-5, it might be that low and high-working memory capacity individuals employ different strategies. Looking back at a location could indicate a rehearsal attempt or preparing for action. In the same vein, designs that aim to precisely dissect eye movements when it is established that the location of the item has been memorised correctly is likely to further provide fruitful insights. Future research should also take into account smaller eye movements into account, specifically when there are multiple items to be recalled, while also designs should aim to separate different biases such as action. The findings presented in this thesis, which illustrate distinct gaze patterns associated with different types of information processing, serve as a crucial step in understanding the interplay between eye movements and cognitive strategies.

As we move forward, the integration of advanced technological tools like virtual reality offers a compelling pathway to delve deeper into these phenomena, enabling more immersive and complex stimuli to be utilized in experimental settings. Recent research has identified virtual reality as an important tool to further investigate the working memory processes and their influence on attention (e.g. Draschkow et al., 2021, 2022). The identified differential gaze patterns, characterized by more precise looks towards items when encoding verbal information and a steady decrease in looks with spatial information, underscore the complexity of cognitive strategies employed during memory tasks. This observation suggests that future research should aim to disentangle the underlying mechanisms that guide these distinct patterns. The employment of virtual reality can significantly contribute to this endeavour by providing a highly controlled yet flexible environment where researchers can manipulate spatial and verbal stimuli with greater precision and complexity. These technologies allow for the creation of more complex and ecologically valid experimental designs that can closely mimic real-world scenarios, thus providing insights into how these cognitive processes unfold outside the laboratory setting. Furthermore, the application of virtual reality in exploring individual differences in cognitive processing extends beyond mere replication of real-world complexity. It opens new dimensions for assessing how individuals navigate and interact with three-dimensional spaces and complex linguistic contexts, potentially unveiling individual-specific cognitive strategies that remain obscured in traditional experimental setups. Indeed, previous research has identified individual differences in preferences of saccadic control, with some participants choosing more, and others less saccadic activity (Laeng & Teodorescu, 2002; Ridgeway, 2006). For instance, immersive virtual reality environments could be designed to study how individuals employ oculomotor strategies in navigation tasks, offering a more detailed understanding of spatial information encoding and maintenance.

5.4 Conclusion

This thesis has advanced our understanding of gaze activity in the context of spatial and verbal information maintenance, providing key insights into the strategic use of eye movements. It builds upon and extends previous findings by exploring the gaze shifts and how these are influenced by the predictability of recall order. It reveals that eye movements play a crucial strategic role, especially in maintaining spatial information, highlighting the close link between oculomotor activity and spatial working memory. This is supported by the observation of increased gaze shifts towards relevant items under unpredictable recall conditions for spatial materials, suggesting the importance of foreknowledge in modulating gaze patterns. Furthermore, the current thesis demonstrates that utilizing long-term memory representations can significantly influence gaze shifts, indicating a sophisticated strategy that integrates spatial layouts to enhance memory performance. This aligns with literature on the impact of expertise on eye movement patterns and points to the dual function of eye movements in cognitive processing: not only preparing for action but also facilitating memory rehearsal. By distinguishing biases towards memorized and action-relevant locations, this work contributes to a deeper understanding of the role of eye movements in memory encoding and maintenance. Notably, throughout this thesis there was no strong evidence for a direct link between gaze patterns to memorised locations and recall performance, which is in line with the idea that these looks are indicative of rehearsal attempts rather than directly boosting recall. In sum, this thesis extends our knowledge of eye movement strategies in cognitive processes and lays the groundwork for future research to further dissect the intricate relationship between oculomotor activity, attention, and memory. It presents a compelling case for the inclusion of eye movement analysis, offering new directions for refining working memory models to account for the interplay between gaze activity and cognitive function.

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Appendix

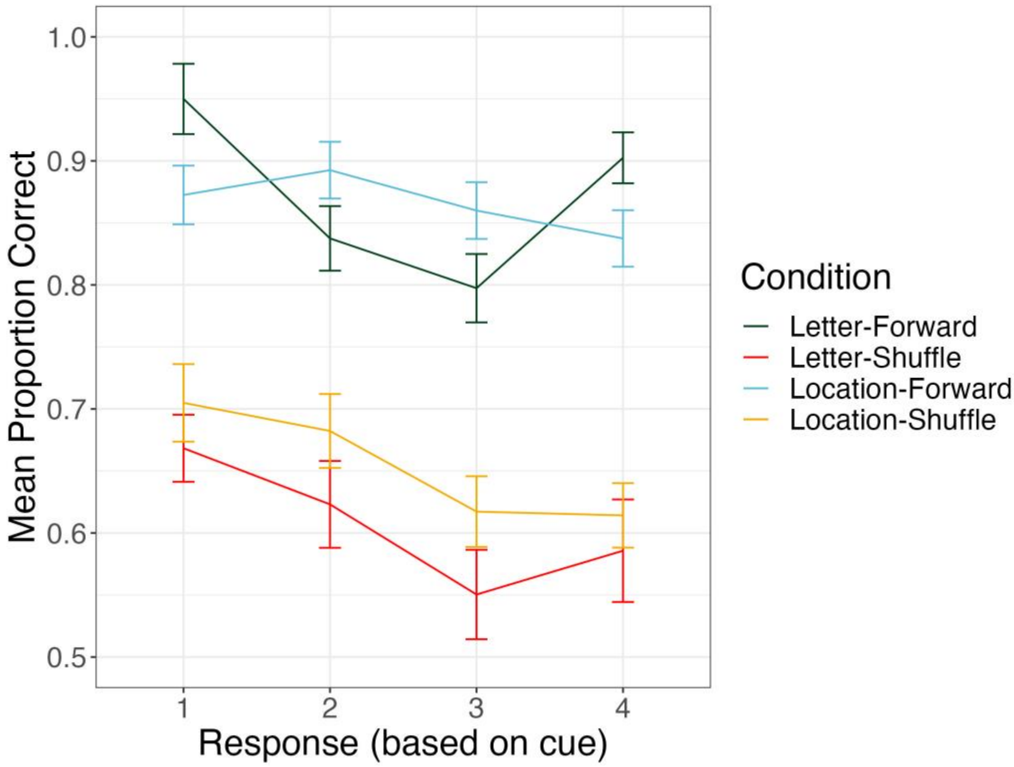

Figure 1 Mean proportion correct as a function of condition (letter-forward, letter-shuffle, location-forward, location-shuffle) and response position (1-4). Error bars mark within-participant standard errors around the mean calculated with the Cousineau-Morey method.

Table 1 Coordinates of digits in Experiment 2 (Experiment Builder; 1920x1080 pixels with 0, 0 being the top left of the screen):

Typical Layout Digit Location	Novel Layout Digit Location	X coordinate	Y coordinate
1	8	480	120
2	1	960	120
3	7	1440	120
4	6	480	400
5	9	960	400
6	3	1440	400
7	2	480	680
8	5	960	680
9	0	1440	680
0	4	960	960

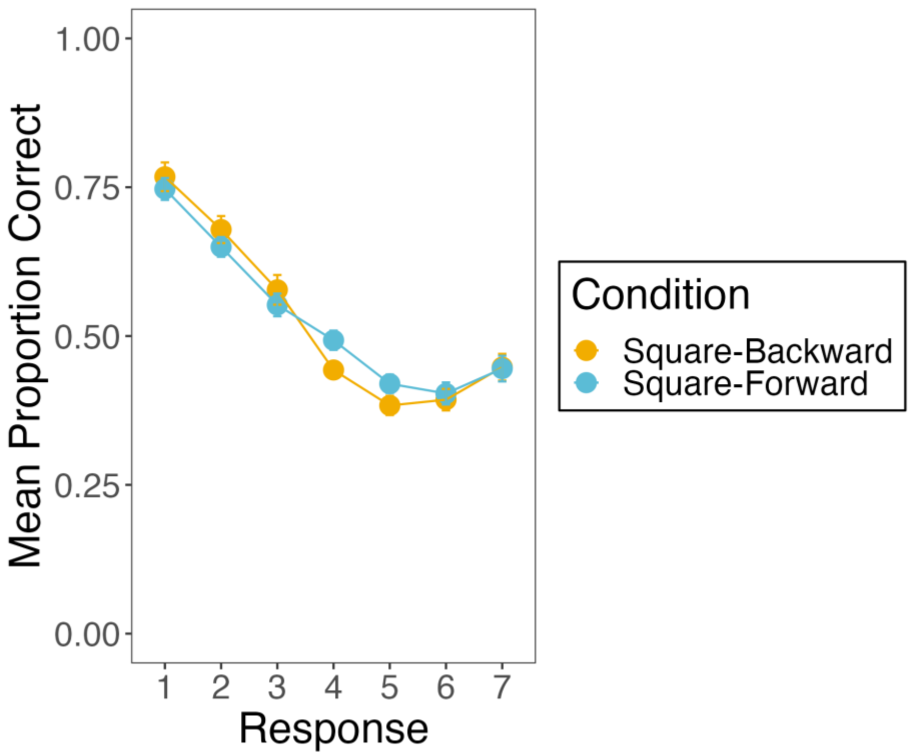

Figure 2 Lenient proportion correct as a function of condition (square-backward and square-forward) and serial position (1-7). These values were calculated based on the distance of the response to the correct square, with a correct response being identified as 1, 1 square away from it having the assigned value of .66, 2 squares having the value of .33, and 3 or more squares away from the correct one being 0. Error bars mark within-participant standard errors around the mean calculated with the Cousineau-Morey method.

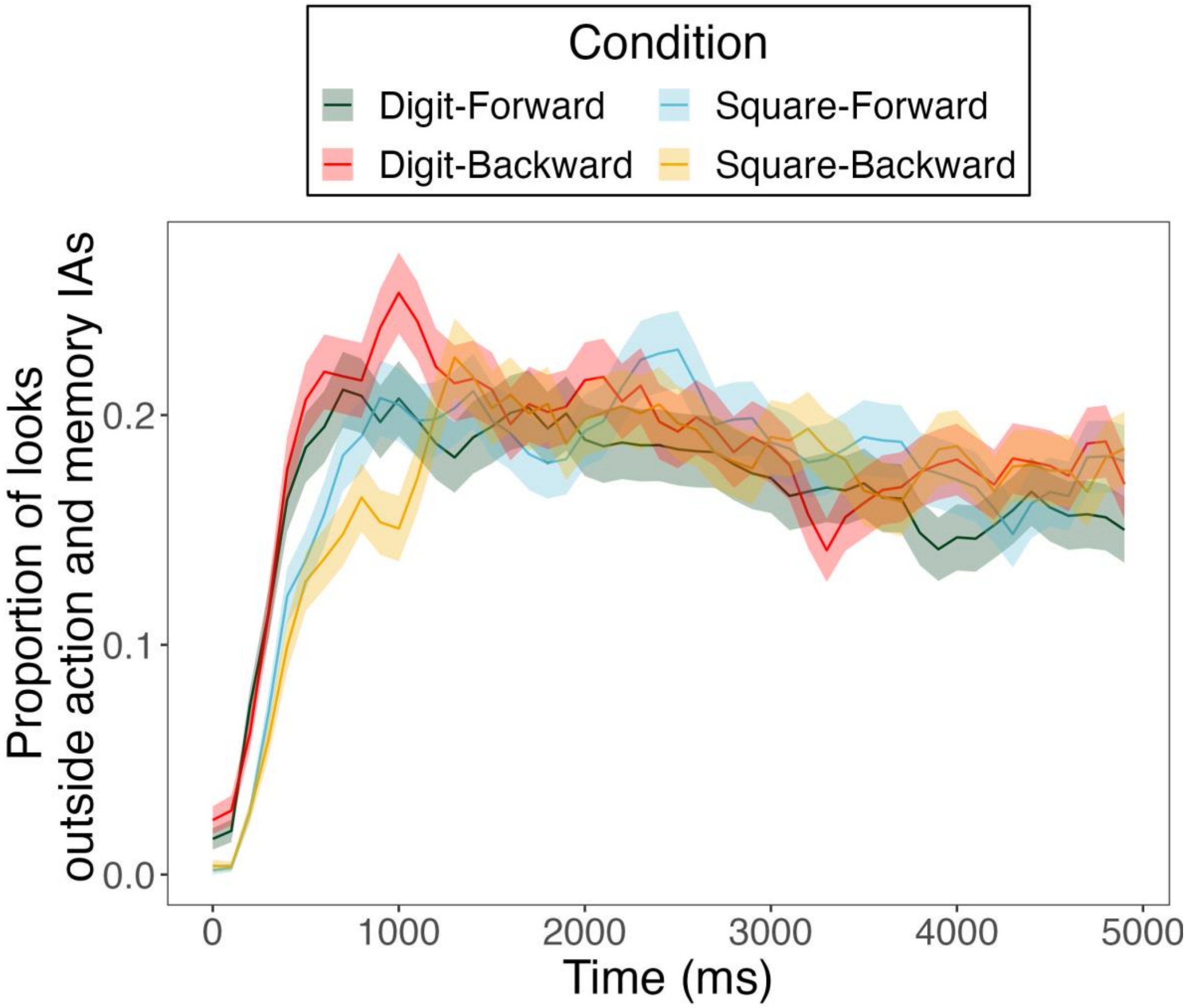

Figure 3 Time course of the proportion of looks outside of the memory and action interest areas across conditions (digit-forward, digit-backward, square-forward, square-backward). Shaded areas represent within-participant standard errors around the mean calculated with the Cousineau-Morey method.

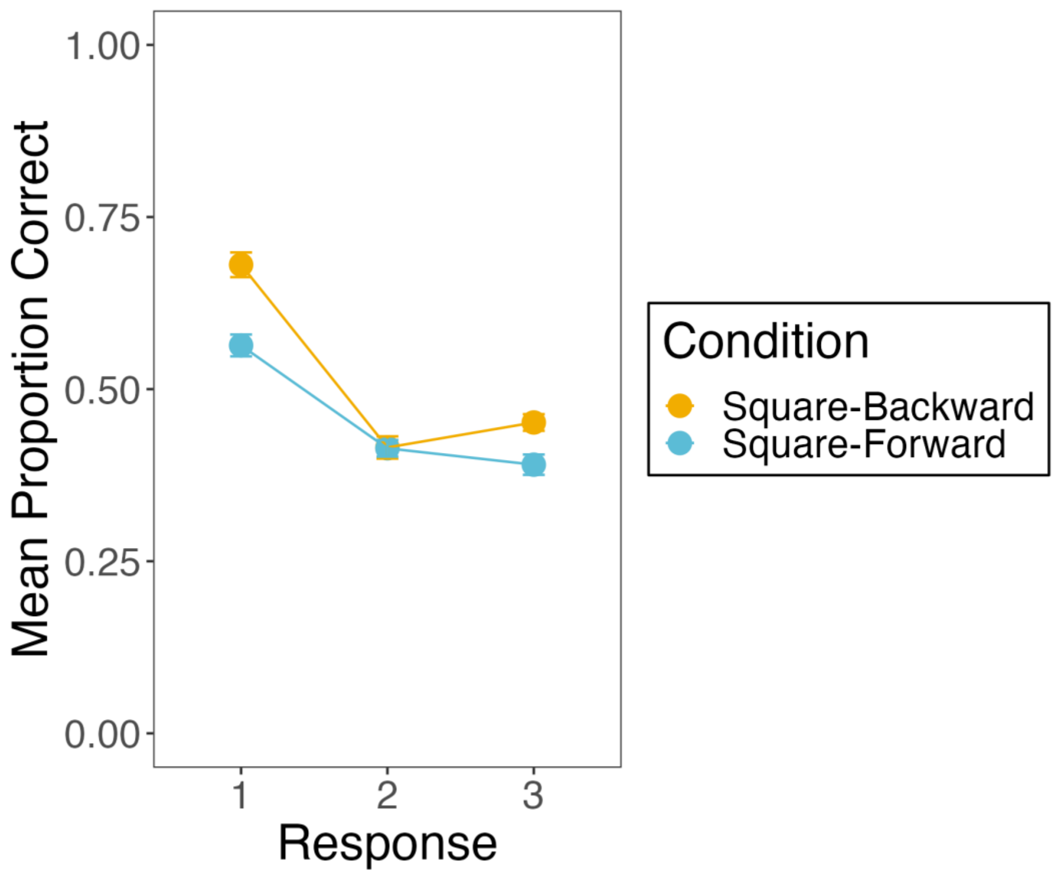

Figure 4 Lenient proportion correct as a function of condition (square-backward and square-forward) and response position (1-3). These values were calculated based on the distance of the response to the correct square, with a correct response based on retro cue being identified as 1, 1 square away from it having the assigned value of .66, 2 squares having the value of .33, and 3 or more squares away from the correct one being 0. Error bars mark within-participant standard errors around the mean calculated with the Cousineau-Morey method.

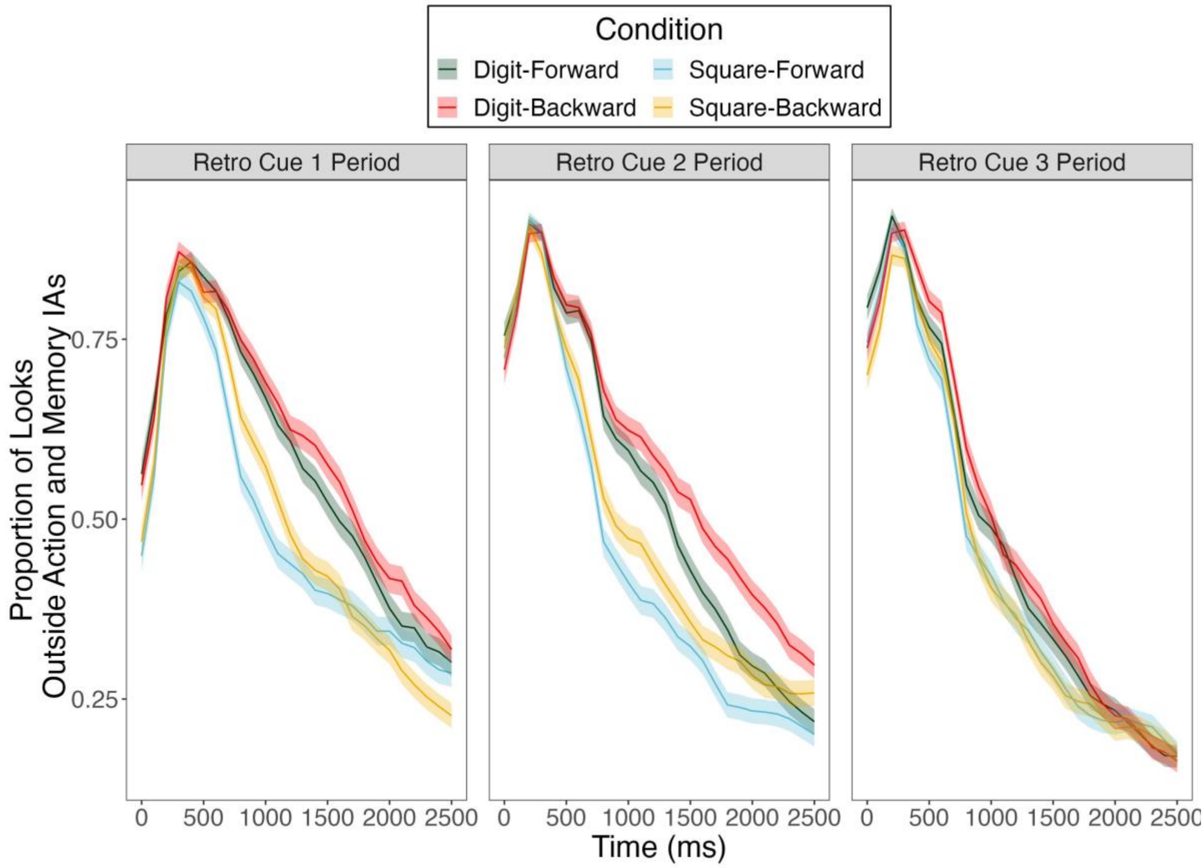

Figure 5 Time course of the proportion of looks outside of the action and memory interest areas across conditions (digit-forward, digit-backward, square-forward, square-backward). Note that the retro cue is displayed from 0ms to 500ms. Shaded areas represent within-participant standard errors around the mean calculated with the Cousineau-Morey method.