The role of working memory content in oculomotor capture

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ABSTRACT

The relationship between working memory and visual selection is close yet, but how working memory contents influence dynamic overt selective attention are unclear. Based on covert attention studies, evidence shows that when memory resources were taxed, increased oculomotor capture by distractors may depend on the overlap between memory-content and search stimuli. In the present study, we used an eye-tracker technique and combined a working memory task with a search task. Memory content was based on color or shape information. The color-preview overlapped with stimulus saliency whereas the shape-preview was not. In the active-memory condition, participants were asked to remember the memory array until the end of trials and did not have to remember in the no-memory condition. In the search task, participants were instructed to make a saccade to a specific-tilted target. Either the target was a uniquered tilted line, or the distractor was red while the remaining non-targets were white. The orientation and color of the target and distractor were opposite. Experiment 1 used a 2 memory-types (active-memory vs. no-memory) * 2 memory-content (color-preview vs. shape-preview) * 2 target-salience (salient-target vs. salient-distractor) within-subject design. The results revealed a reliable three-way interaction among memory-content, memory-type and target-salience, suggesting the influence of color-saliency was larger for the color-memory compare to the shape-memory. The post-hoc follow-up test further indicated that saliency processing was enhanced by color-memory. The difference between the salient target and non-salient target as a function of memorytype was greatly large only for the color-preview. Thus, to further investigate the effect of the color-preview, Experiment 2 was designed where only the color-preview and the no-preview were presented. The results showed that the three-way interaction among preview-memory, target-saliency and experiment-type was not reliable, suggesting that the difference as a function of target-saliency between color-memory and color-preview no-memory in Experiment 2 was similar to Experiment 1. While ignoring the nopreview, more saliency-driven saccades were observed when memorizing the colorpreview. Additionally, the bin only interacted with target-saliency in both experiments. Taken together, oculomotor capture by saliency could be enhanced by active-memory only when it matched to memory-content. While the time-course of overt selection was influenced by stimuli salience, working memory did not modulate such dynamics.

Key words Working memory, Selective attention, Visual selection, Eye movements

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CHAPTER 1 – INTRODUCTION

The present study aimed to determine how working memory contents direct saccadic eye movements to targets as a function of saccade latencies. Another purpose of this research was whether physical salience in the visual environment could mediate such memory-based oculomotor capture. Although the effect of working memory content on covert attentional capture has been extensively discussed in previous literature reviews, there is debate as to whether memory content has a guiding or inhibiting effect on the processing of targets or distractors. In addition, its role in dynamic overt oculomotor capture is also unclear.

Working memory, described as the mechanism and process that maintains the upto-date mental representations required for processing for ongoing cognitive tasks (Cowan et al., 2018), has attracted a great deal of attention in recent years. There is growing evidence for a strong link between attention and working memory (Baddeley, 1993; Chun, 2011; Cowan, 1999; Gazzaley & Nobre, 2012; Kane et al., 2001; Oberauer, 2019), including filtering perceptual information into working memory (Sander et al., 2011; Ueno et al., 2011; Vogel et al., 2005), selective retrieval from long-term memory (Oberauer et al., 2017), and removal of information from working memory (Hasher et al., 1999; see also review Lewis-Peacock et al., 2018). Since Jonides and Yantis (1988) reported that the sudden onset of a single item during visual search would attract attention (i.e., attentional capture), increasing research has explored the underlying cognitive mechanisms that determine attentional capture (Yantis, 1993). Although it has been claimed that only task-relevant features capture attention (Folk et al., 1992), Schreij et al. (2008) found that task-irrelevant emergencies initially capture attention, even if observers hold a goal-relevant attention set (Belopolsky & Theeuwes, 2009; Theeuwes, 2010). Therefore, it is crucial to identify whether salient but unrelated features of objects have different attentional capture effects. In the context of visual working memory, there are many different explanations for the effects on covert attentional capture while there has been little research on overt oculomotor capture

(Marshall & Bays, 2013; Palangi et al., 2016; Yu & Shim, 2017). Thus, the potential correlation between visual working memory and oculomotor capture is a pressing issue.

Visual scenes often contain more information than our visual system can process at any given moment (Koch & Caldwell, 2006). Thus, the attentional mechanism is beneficial for further processing relevant objects and suppressing those that are not relevant to the current goals (Mulckhuyse et al., 2008; Soto et al., 2005; Steven Yantis, 2000). Selection is thought to occur in two ways. The deployment of attention may be biased in a bottom-up manner, leading to the automatic localization of the salient but task-irrelevant stimuli (Theeuwes & Burger, 1998; van Zoest & Donk, 2004, 2005; Steven Yantis & Hillstrom, 1994), or guided by internal goals requiring cognitive control in a top-down manner (Corbetta & Shulman, 2002; Hopf & Mangun, 2000; Siebold et al., 2011). This is the difference between voluntary and involuntary distributions of attention (Shiffrin, 1997). More recently, it has been suggested that bottom-up attention also includes the influence of what we have learned. For example, when the item is task-relevant as what we have learned before, it can capture attention (Awh et al., 2012; B. Wang & Theeuwes, 2018).

The link between attentional selection and working memory has been extensively studied, including how working memory influences both covert attentional selection and overt oculomotor selection based on various paradigms and tasks, such as the dualtask paradigm, the oculomotor capture paradigm, or the gaze-correction task (e.g., Watson et al., 2019). Corresponding data analyses used various attentional indexes such as reaction time, search accuracy or initial saccade orientation and saccade latency. However, pupil size as one of the important cognitive indicators was ignored. More importantly, most of the published articles have discussed the association between memory content and covert attention, but the effect on overt oculomotor capture is currently unknown.

1.1 WORKING MEMORY IN COVERT ATTENTIONAL SELECTION

1.1.1 Distractibility by Working Memory

Numerous studies have shown that working memory is critical for optimising selective attentional performance. Most of them have typically employed a dual-task paradigm, combining a visual search task with a working memory task, to investigate how different factors affect attentional selection when working memory was involved (Lavie, 2005). The assumption that working memory and attentional control share a limited attentional resource with unidimensional, non-specific features are typically relied on. In this case, substantial costs of dual task are expected to be higher when the current task requires both attentional control and working memory maintenance in combination. There is much evidence for such dual-task costs demonstrating that working memory increases distractibility, such as increased attentional capture by taskirrelevant stimuli in a flanker task (e.g., Kelley & Lavie, 2011; Lavie et al., 2004) and a visual search task (e.g., Han & Kim, 2009; Soto et al., 2005).

Most research supports the idea that high memory load enhances the disruption of attentional capture by irrelevant-but-salient distractors in visual search (de Fockert & Theeuwes, 2012). For example, people were asked to maintain a digital array in working memory until the end of the trial. Following the visual search task, they were instructed to search for a uniquely shape-defined item during visual search. In some trials, an additional color-defined singleton appeared. The search for a target defined by the shape was slower when one of the non-target singletons had a unique feature in the color dimension, even though the color remained a task-independent feature dimension throughout the experiment (Theeuwes, 2010). This interference with attentional capture becomes more pronounced especially when memory load levels are increased (e.g., Lavie & De Fockert, 2005; Lavie & de Fockert, 2006). However, attentional capture cannot always be modulated by memory load but is more dependent on physical salience in the visual fields (de Fockert & Theeuwes, 2012). The stronger neuronal activation responses in the inferior frontal cortex that account for the attentional deployment were found when attention was allocated to less salient distractors. This implies that the impacts of working memory on attentional capture are moderating by relative saliency in the visual environment.

1.1.2 Working Memory Content in Attention

There is growing evidence that working memory based on different content has different effects on attentional capture. Some studies have proposed that the interference of distractors with attentional selection depends largely on whether the processing of the target or distractor in the search display overlaps with memory content (Park et al., 2007). For instance, Kim et al. (2005) used a Stroop task in which people were instructed to remember a group of letters. While the words were targets in the same modality as memory contents, the color of words was an irrelevant distractor in a different modality from memory content. Compared to the targets in a different modality, when they had to identify the words' meaning rather than the words' color, it increased the processing of the unrelated color of the Stroop color words. Conversely, it reduced the processing of irrelevant words when attention had to be drawn to color rather than its meaning. The results suggested that the processing of distracting words could be reduced when the target and working memory content were different modalities, even when the memory load was taxed. In turn, an increase in the processing of distractors could be observed when the target and memory content was the same modality, even when memory resources were presumably available.

Other studies have also reached similar conclusions. In the experiment by Park and colleagues (2007), people had to remember faces or houses before preforming the selective attention task. They were asked to focus on faces while avoiding interference from houses on some trials, and vice versa. It was found that if the search target and memory content had the same modality (e.g., remembering faces and searching for faces), processing of house information as a distractor was enhanced. However, when working memory content and search targets had different modalities (e.g., remembering faces and searching for houses), face information processing as a distractor was less frequent. The results suggest that if the loaded memory content modality overlaps with target processing, increased processing of distractors can be observed. Conversely, if the memory modality differs from the target processing, there is a decrease in distractor processing.

1.1.3 Controversy of Memory Content in Attention

The effects of memory contents on selective attention are noticed in above mentioned studies on memory load (Greene et al., 2015; Zhang et al., 2010). The question of how and when the content of working memory itself directs attention remains controversial. It is generally accepted that when a target template is present in working memory (de Fockert et al., 2001; Downing, 2000; Soto et al., 2005), attention can be guided by memory representations to process more items with the same features as the target in the visual scene (Desimone & Duncan, 1995; Wolfe, 1994). Thus, the information in the visual environment that has similar features to those stored in working memory can attract more perceptual attention so that its processing is enhanced. Such memory-guiding effect can occur not only for spatial information (Awh et al., 1998) but also for feature-based information. An important finding was in a study on the effects of attentional capture during visual search, which revealed the priming effects of content-matching stimuli (Olivers et al., 2011). In this study, participants were instructed to maintain an item (e.g., a color or a color word) in working memory. The visual search task was performed after the memory display disappeared. Stimuli that matched information stored in working memory in the search display can capture more attention (Soto et al., 2008).

However, there is an issue of whether such content-based guidance occurs automatically or more strategically. Since the findings of Downing (2000) first suggested that attentional selection can be directed by memory contents automatically, other studies (Soto et al., 2005; Oberauer, 2009) also found that representations maintained in working memory direct attention involuntarily. For example, in the fourth experiment by Soto et al. (2005), colored-shaped placeholders that had the same features (i.e., color or shape) as the memory prime were presented, which contained a distractor on invalid trials. A target was included on valid trials. The memory prime was not identical to any feature of the placeholders on neutral trials. They found that participants reacted faster to the visual search task on neural trials than on invalid trials, suggesting that attention can be involuntarily directed by memory content. Attention could be attracted by the memory-matching item even when the item matched the memory content was a task-irrelevant distractor (Forester et al., 2019; Palangi et al., 2016; De Houwer et al., 2017). The theory of biased competition has also proposed an alternative interpretation that when searching for a given target in a visual scene, search templates held in working memory can moderate attentional selection involuntarily so that items matching the memory template are prioritized (Conci et al., 2013; Folk et al., 1992; Hollingworth, 2012; Vogel et al., 2006; Wolfe, 1994).

Nevertheless, recent studies have challenged the view that working memory content can only elicit automatic attentional shifts. They argued that memory content can be used more flexibly and strategically during attentional selection to facilitate the activation of memory-matching target processing and the inhibition of memorymatching distractor processing (Hu et al., 2011; Kiyonaga & Egner, 2014; R. Sawaki et al., 2012; Risa Sawaki & Luck, 2011). For example, Woodman and colleagues (2007) adapted experiments from a study by Soto et al. (2005) but did not find that working memory content can increase the likelihood of attentional capture by memory-matching items. Instead, the opposite phenomenon was observed, which is the suppression of memory-driven effects (Olivers et al., 2006). In the experiment by Downing and Dodds (2004), participants were asked to perform a visual search task within the interval of retention after remembering memory cues. One distractor with the same color as the memory cue was presented in the visual search display on half of the trials, while no search item with the same feature as the memory on the other half of the trials. They found that when distractors with the same features as memory cues were present during visual search, even better search performance for the target and shorter reaction times were obtained than when the search stimulus did not overlap with the memory content. Interestingly, the expected reduction in target search time was not observed when the search target was the same color as the memory cue with very low probability. They concluded that working memory content does not necessarily lead to automatic attentional selection but can be used more flexibly to improve search performance. Some researchers have argued that when memory content is never matched with the memory cue, a so-called "rejection template" is generated in the cognitive environment based on the content of working memory. It diverts attention away from the distractor location containing the memory content (Downing & Dodds, 2004). Other behavioral studies have further found that search performance can be improved when distractors and memory contents are predictably matched (Arita et al., 2012; Han & Kim, 2009; Sala & Courtney, 2009). The deployment of attention appears to be more strategically biased by working memory content under cognitive control.

However, Olivers (2009) proposed the alternative probability that the inhibitory effect of memory content on distractors previously observed by Woodman and Luck (2007) was not based on top-down strategic processing, but rather a bottom-up approach. Subsequent studies have supported this claim (Koelewijn et al., 2008; Nieuwenstein & Potter, 2007). For instance, in a study by Nieuwenstein and colleagues (2007), participants were required to identify two letter-defined targets from a rapid stream of digit-defined distractors. Before presenting the distractor flow, the working memory task required remembering an array containing three letters. Each target letter in the stream could be matched to an item stored in memory. Surprisingly, the results revealed that when any letter of the target letters was the same as the letter in memory, the rate of target omission increased. Not only that, but they also found that there was no decrease in the probability of attentional capture by these distractors when observers were explicitly instructed that distractors matched the memory and had to be ignored. This explicit instruction appeared to divert attention more from the target and draw it to the distractor rather than ignoring them (Lamy et al., 2003). The results suggest that attention was captured by memory-matching items compulsively even though participants knew that the items in memory were never relevant to the task, implying that the memory-based priming effect is an automatic process (Olivers, 2009; Soto et al., 2005, 2006, 2008).

1.1.4 Interim Summary

Overall, there is conflicting evidence about whether and how the content of working memory influences visual attentional selection. However, most of these studies have focused on the covert component of attentional selection such as manual responses to measure performance, which relies on inferences about the deployment of attention in space (Downing, 2000; Hollingworth et al., 2013). In general, shorter response times to the target are described as being associated with effective top-down control, whereas longer reaction times to the target are thought to be associated with increased processing of distractors, leading to a cost in reaction time. But in cases where both salient-driven and target-driven processing are present, attention may be distracted from the target by the salient distractor. This extra attentional shift would cause a longer manual response time to the correct target and undisturbed target selection (Theeuwes, 1992). Only the manual response delay to a target is considered to be interference from irrelevant distractors in covert attention. In contrast, eye-movement studies provide a very straightforward measurement. In the above case, if a salient distractor is detrimental to target selection, then in the eye-movement data, it will be immediately manifested as an inaccurate initial saccade. (e.g., Theeuwes et al., 1999; Theeuwes & Burger, 1998). Thus, compared to the overt oculomotor selection, indicators reflecting covert attentional selection, such as reaction time, maybe not intuitive enough.

In addition, there is little information about the underlying temporal dynamics selected in covert measures. Previous studies have also proved that the factors determining attention selection may be different in different periods (e.g., van Zoest & Donk, 2004). Unlike covert mechanisms, overt orienting is associated with observable saccadic eye movements and pupil size changes (Frischen et al., 2007; Wright & Ward, 2008). The attribute provides a window into potential and ongoing processes for selection (Van Zoest & Donk, 2006). More specifically, eye movements recordings can measure the landing position for each millisecond from the memory display to the final manual response. Eye movements can therefore provide direct evidence of how visual selection is influenced by working memory content in this way and related to the final memory performance.

1.2 WORKING MEMORY IN OVERT OCULOMOTOR SELECTION

From the studies on covert attention, it is clear that the association between working memory content and stimulus in search displays is a critical factor ofr attentional selection. However, research on the relationship between memory content and oculomotor capture is unknown yet. Early studies on eye movements have shown that abrupt onset (Schreij et al., 2008; Theeuwes, 1994; Theeuwes, 1991, 1995; Theeuwes et al., 1999; Theeuwes & Burger, 1998) and irrelevant-but-salient items (Walker et al., 1997) can exogenously capture attention and elicit longer saccade latencies. Resource-dependent executive-control processes can modulate the overt oculomotor capture by irrelevant-but-salient items in visual search, which has been demonstrated primarily through direct manipulation of working memory load levels (e.g., Hester & Garavan, 2005; McCabe et al., 2010). However, studies that directly modulate memory content do not yet exist.

1.2.1 Orienting of Saccadic Selection

There is a strong link between working memory, attentional selection and eye movements. Commonly, locations that would be attended to attract saccades while potential saccadic targets can in turn attract attention, suggesting a correlation between saccades and spatial attention (Hoffman & Subramaniam, 1995; Kowler et al., 1995). Schneider et al. (2002) summarized the three-way link that attention precedes saccades and is a tool for maintaining representations in working memory (Godijn & Theeuwes, 2004). A saccade to the location being attended is preceded by a covert shift of attention to that location, allowing eye movements to provide a good index of attention online (Deubel & Schneider, 1996).

The time-course of overt oculomotor selection is highly idiosyncratic. Current research suggests that in the visual environment, oculomotor selection is controlled in two ways, namely stimuli-elicited and target-directed (Van Zoest et al., 2007). In other words, stimulus-sensitivity mainly determines early eye-movement selection, whereas later oculomotor selection is based on the target and intention of observers (van Zoest & Donk, 2004). Typically, the initiation latency of saccades guided by the current target is increased compared to saccades elicited by the physically salient features. In a classical experiment using the oculomotor capture paradigm (see Figure. 1A), one is asked to move a saccade to a predefined target with a salient color (Theeuwes & Burger, 1998; Theeuwes & Godijn, 2002). In this paradigm, six grey circles are distributed around the imaginary circle in the search display in this experiment. After a given period, all but one of the circles turn red in color. One is asked to saccade to the only grey circle that remains similar in color to the previous one. Additionally, an additional red singleton is also shown in the visual display with the color of distractors' color changes simultaneously in half of the trials. Participants have been told before the search display that the extra salient distractor is always task-irrelevant. However, more saccades are significantly attracted to the irrelevant onset distractor than to the grey target (Theeuwes & Godijn, 2002). Oculomotor capture is thus defined as the involuntary and incorrect saccades to a new onset location even when the individual is explicitly instructed to look for a pre-specified colored singleton. During the timecourse of overt-selection, saccade latencies can accurately show that the oculomotor capture is much faster for irrelevant-but-salient distractors than for targets (Hunt et al., 2007; Theeuwes et al., 1999; Theeuwes & Godijn, 2002).

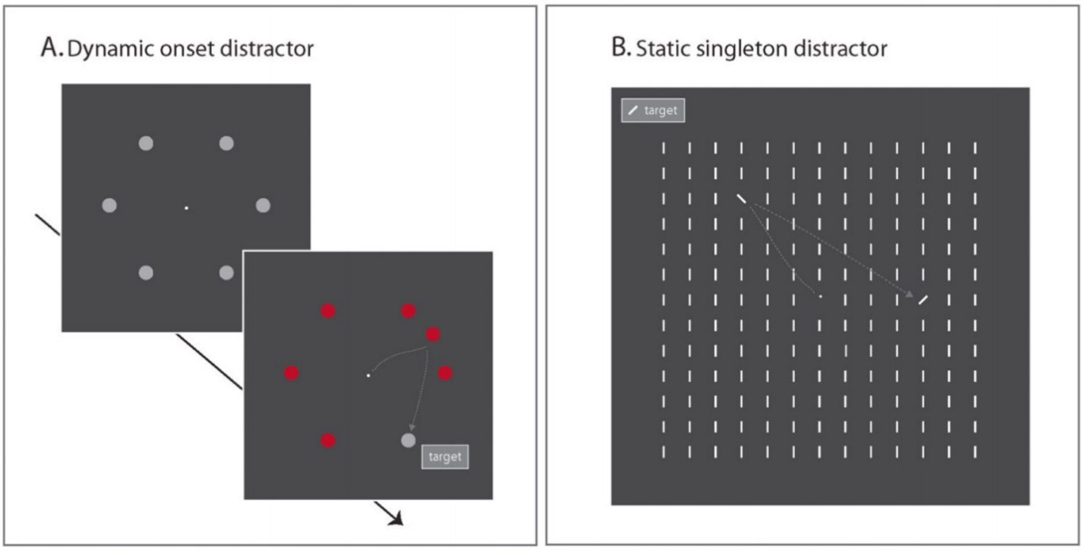

Figure 1. Taken from a review by van Zoest et al. (2017). (A) The paradigm of additional onset singleton as an example. Saccadic movements are captured by a salient distractor that is displayed as an abrupt onset. (B) A static distractor in the additional singleton task. A target and distractor would be presented in opposite directions and sometimes colors. In this example, the saccadic movement would be initially erroneously guided toward a task-unrelated distractor, and then correctly captured by the target.

Current research suggests that in the visual environment, oculomotor selection is controlled in two ways, namely stimuli-elicited and target-directed (Van Zoest et al., 2007). In a study by van Zoest and colleagues (2005), the static saliency of a singleton was found to be similarly time-dependent to that of a continuously varying distractor. Targets were presented in three contexts, in direction or sometimes color, with targets less salient than, as salient as, or more salient than distractors. Accurate saccades to target was subsequently analysed as a function of saccade latencies to reveal the relative contributions of the stimuli-directed and goal-directed controls over time. Consistent with previous studies (Theeuwes & Burger, 1998; Theeuwes & Godijn, 2002), saccades were often mis-attracted by the position of distractors with unrelated-but-salient features. However, by using these specific displays with varying degrees of stimulus saliency, this relative saliency of the singletons only affected the oculomotor search for short saccade latencies. In particular, the initial saccades elicited shortly after the search display was presented eventually fell on the most salient singleton. Thus, oculomotor capture by the target was found when the target was the most salient item, which was an improvement in search performance. In turn, when irrelevant distractors were the most salient, eye movements would end up on the location of distractors, which was a reduction in search performance. However, this relative-salience effect was not observed when initial eye movements were evoked during longer saccade latencies. During longer latencies, eye movements were more accurately attracted to the target regardless of the salience distribution across the visual field. These saccades are thought to be increasingly target-directed (Heimler et al., 2014, 2015; Van Zoest & Donk, 2008).

1.2.2 Process of Saccadic Selection

Saccadic processes in attentional selection is also controversial in terms of how they are driven, either voluntarily or involuntarily. There is evidence that stimulus saliency does not facilitate saccades to select locations containing salience voluntarily during the later stages of visual search (Van Zoest & Donk, 2008). Specifically, in some trials, the target was the most salient among all visual environment elements, but only short-latency saccades landed precisely at the location of the target with the most salient features. In other words, when the salience of the stimulus was relevant to the task, saliency information could not be used to guide eye movements even when observers had sufficient time to voluntarily select a landing position. This also suggests that the effect of saliency decreases over time, regardless of whether voluntary processing directs saccadic selection online. These findings demonstrate that involuntary oculomotor capture may be elicited at early stages and that initial saccades are directed to salience, irrespective of its relevance. Moreover, the early bottom-up effect of oculomotor capture would compete with later saccades that are more strategically oriented toward task-relevant items. Thus it is possible that only late saccadic selection is influenced by top-down saccades (van Zoest & Donk, 2005).

1.2.3 Working Memory Contents in Saccadic Selection

Many recent studies have used eye-tracking to investigate the effect of working memory content on oculomotor capture (Carlisle & Kristjánsson, 2018; Lu et al., 2017; Soto et al., 2005). A synthesis of previous studies shows similar contradictory evidence to those reported on covert attention. The debate focuses on whether overt oculomotor deployment is biased by working memory content in an automatic or non-automatic manner, and whether it occurs at an earlier stage or at a later time.

Evidence from several studies suggests that saccades can reflect a strong link between overt oculomotor selection and visual working memory (Cronin & Irwin, 2018; Johnson et al., 2008). Converging evidence is provided by a gaze-correction study (P. Watson et al., 2019), which investigated effects of the secondary working memory task on feature-based saccades. In the primary task, participants were asked to perform saccades to specific discs from colored disks arranged in a circular pattern. In some trials, the array was rotated during visual search so that the saccade was directed to a location between a distractor and a target with another colored feature (Hollingworth & Luck, 2009). The results showed that with the presence of memory-matching distractors, a large proportion of correct saccades were directed towards the distractor rather than the target (i.e., oculomotor capture). In addition, the mean latency of the correct initial saccade towards the target slowed, representing competition from the distractor. These effects suggest that memory-matching items can capture overt attention even when the features held in working memory are not task-relevant.

There is also growing evidence that working memory content can involuntarily lead to overt oculomotor selection at an early stage. Given that the information is stored in memory, memory-biased covert attentional selection may occur automatically, without any intention or goal of the observer (Soto et al., 2008). The association between visual selection and working memory content is also evident in oculomotor capture. Initial saccades displayed in visual search can be automatically drawn to objects that are not task-relevant but memory-matching. When distractors were matched to features of information stored in working memory, there was less initial saccade to correctly orient the search target compared to a neutral baseline where no search items overlapped with the memory content (Soto et al., 2005). These findings suggest that the early overt oculomotor capture by memory-matching stimuli is involuntary and obligatory (Olivers et al., 2006). Soto and colleagues (2010) further provided reliable evidence that stimuli matching the color dimension of working memory content modulated oculomotor capture at an early stage. This is consistent with previous findings. Even when working memory content is damaging to performance, visual representations held in memory can influence initial saccade orientation and saccade latency in search. Thus, working memory content can mediate early automatic oculomotor capture in a top-down manner (Mannan et al., 2010).

While working memory content can automatically bias the direction of overt oculomotor selection in the early stages, this memory-based effect can also be used more flexibly over time. Previous research have found that working memory content inhibits oculomotor capture and have proposed that memory content can strategically guide saccades by manipulating the probability of memory-matching distractors or by varying the number of search items (Hu et al., 2011; Kiyonaga et al., 2012; Lu et al., 2017; Risa Sawaki & Luck, 2011). For instance, Lu and colleagues (2017) used a dualtask paradigm combined with the eye-tracking technique to manipulate the likelihood of memory-matching distractors. It was found that inhibition of oculomotor capture by distractors was observed only when working memory content was matched with distractors with high probability. In contrast, when distractors were matched with memory content with low probability, more eye movements were directed to distractors. These findings indicate that working memory content guided involuntary oculomotor capture during early visual search. Given sufficient experience with distractors after competition resolution, the guidance of attention by working memory content can be controlled strategically. Thus, this overt oculomotor selection guided by the content of working memory might involve multiple cognitive processes. Oculomotor capture by distractors and targets occurs in different time-windows when a possible distractor can be predicted to appear at the following onset location. More memory-driven guidance effects occur automatically in the early stages (Berggren & Eimer, 2018; Hickey et al., 2010), whereas in later stages, there are more inhibition of distractors (Gaspelin & Luck, 2018; Goujon et al., 2015; B. Wang & Theeuwes, 2018).

1.2.4 Speculations for Working Memory Contents in Saccadic Selection

To reconcile the conflicting findings, researchers have put forward some hypotheses to explain the cause. One speculation is that the information held in working memory may remain active or accessory. It claims that in an ongoing task, only active items could affect the deployment of attention. In the visual search task, when memory objects are not needed during visual search, these objects may be excessively or passively stored and thus fail to direct attention. However, to manifest memory-driven effects, items held in working memory may have to remain active. For example, Attention is automatically biased towards memory-matching objects when search targets are matched to memory content at a high rate or need to be maintained until the end of the trial (e.g., Woodman & Luck, 2007). It takes time for memorized items to change from an active status to passive state. This time is too short for attentional capture to be observed (e.g., Han & Kim, 2009), which is also consistent with some studies proposing template-rejection strategy. The effect is not considered to be an early automatic process, but rather a later compensatory and voluntary behavior following the initial oculomotor capture (Beck et al., 2018; Moher & Egeth, 2012).

Also note that issues about the validity of different features or modalities of items held in working memory can be ignored or inhibited. That leads to a situation where one feature of the memory content is defined as a modality of the search target (e.g., shape), while a feature of another dimension (e.g., color) is defined as a modality that is not relevant to the search or even a search interference (Luck & Vogel, 1997; Marshall & Bays, 2013; O’Craven et al., 1999; Shen et al., 2013). When memory tasks present items with binding features, including color and shape, all features in working memory content can be actively retained. Research has argued that it is not possible to ignore task-irrelevant features stored in memory content and select only those objects that match predefined target features (Forester et al., 2019). When participants held a search target of shape (e.g., a pot) with a task-irrelevant color (e.g., red) in working memory, they made saccades to distractors matching the task-irrelevant color (e.g., a red glass) more frequently and faster. These findings suggest that visual attention is involuntarily biased by items held in working memory that match task-irrelevant features when there is more than one specific dimension.

There are conflicting findings in studies on oculomotor capture similar to those in studies on covert attentional shifts. The main question is whether the role of working memory in facilitating target processing and inhibiting distractor processing depends on automatic or strategic processes. In attempting to answer this question, several points should be taken into account. First, there is evidence from overt oculomotor selection for the role of time-course in the selection process, with early automatic guidance of working memory content, and later strategic deviation from the information held in memory content. Second, representations in working memory may be retained in both active and passive states, and it takes time to transfer memorized items to the passive state. So covert attentional capture cannot be observed in a short period. Finally, the specific features of objects stored in working memory can also influence the effect of memory content. Distractor information processing with irrelevant features is enhanced when more than one features are maintained in working memory.

In summary, the purpose of the present study was to investigate the effect of working memory content on oculomotor capture in the visual environment with relative salience, while considering the role of the time-course factor. This effect would be investigated as a function of saccade latencies. Therefore, a modified oculomotor capture task was employed in the experiments, where the stimuli were simple lines in different orientations. As shown in Figure. 1B, unlike previous research (van Zoest & Donk, 2004), in our experiments, saliency is specified by a unique feature on the color dimension (e.g., a simple red line tilting to right is referred to as a distractor).

1.3 STATEMENT OF PROBLEM

As many studies have demonstrated, both covert attention and overt oculomotor may be drawn to salient visual stimuli. However, the main question remains as to what methods or factors can be used to reduce the interference of those task-irrelevant distractors and attend to the target to improve search performance. Previous research on covert attentional capture has shown that resource-dependent executive-control processes, such as working memory, can help reduce interference from salient-butirrelevant distractors (Burnham et al., 2014). Specifically, in addition to salient stimuli, correlations between stimulus features and working memory content affect the extent to which they capture attention (Greene et al., 2015; Zhang et al., 2010). However, no studies have yet provided direct evidence for overt oculomotor selection. The current study therefore sought to examine how working memory content affects overt oculomotor capture and whether it can mediate the interference from task-irrelevant but salient stimuli.

Interference from salient-but-irrelevant distractors is enhanced in the dual-task paradigm where a working memory task and a visual search task are combined (Boot et al., 2005; Hester & Garavan, 2005; McCabe et al., 2010). For example, Lavie and colleagues (2005) combined a visual search task containing an additional singleton with a working memory task in their experiments (Lavie & De Fockert, 2005). During visual search, observers were instructed to find a circle within a diamond and then to respond to the orientation of the singleton within the target circle. In some trials, a colored singleton was used as a distractor in the search display. All but one of the diamonds were green, while the rest of the shapes were red. The results showed that participants' responses to the target were significantly delayed when the salient singleton distractor was presented (Theeuwes, 1992). In addition to the increased response latency, a more important finding was that target search performance was significantly reduced when memorizing a five-digit array compared with when only one digit needed to be remembered. It appears that working memory tasks are competitive. Attentional capture is affected by executive resources. Thus, the use of executive-control process may reduce the likelihood of attentional capture by salient-but-irrelevant distractors (de Fockert, 2013).

In many studies using this dual-task paradigm, we have found that the correlation between search stimulus and working memory content plays a crucial role in covert attentional capture (Forester et al., 2019; Olivers et al., 2011). In general, individuals must retain an item in working memory before presenting a search display. When visual search tasks are performed within memory retention intervals, memory-matching stimuli involuntarily attract more attention (e.g., De Houwer et al., 2017; Forester et al., 2019; Palangi et al., 2016). For example, Soto and colleagues (2008) found that response times were much faster when the desired search target was located at a position containing a memory-matching color ('valid' trials), compared to both when there was a distractor located at a position containing a memory-matching color ('invalid' trials) and when the memory-matching color was not present ('neutral' trials). Thus, it appears that the memory content in the color dimension affects the probability of automatically attracting attention.

It is worth noting, however, that memory-matching items do not necessarily always attract attention. In this case where items in working memory and targets in a selective attention tasks are of different modalities, the likelihood of attentional capture by distractors can be reduced even when executive-control resources are taxed by the working memory task (S.-Y. Kim et al., 2005). For example, when items held in working memory featured faces, the likelihood of attention capture by distractors featuring faces was reduced. Search performance for targets featuring buildings improved even when working memory resources were presumably unavailable. Conversely, when targets had a single dimension with the same features as the memory content, distractors from other modality were processed even when working memory were presumably available. It seems that whether working memory content increases interference from distractors or improves search performance depend largely on whether the stimuli features are the same as memory content. It is therefore important to know whether memory content contributes to reducing the effect of physical saliency on overt oculomotor selection when the capture is opposite to the current target.

Based on this, one prediction of the present study is that when items in competing working memory tasks and distractors in selective attention tasks involve the same features (e.g., both are colors), working memory would be more involved in reducing interference with color-related distractors, even when executive resources are taxed and presumably unavailable. In contrast, the processing of distractors in modalities other than memory (e.g., color and shape) would be enhanced even when working memory is presumably available. Other studies on the inhibitory effects on distractors have reported that when attentional capture by distractors is inhibited when the likelihood that the distractor is identical to the memory content is high. The present study also sought to investigate whether memory content modulates the effect of salience on oculomotor capture.

Furthermore, a large body of research has shown that working memory content can guide attention in two ways: in an automatic and static process in the early stages, or a more flexible and strategic later. Previous eye-movement and electrophysiological studies have investigated the effects of memory content on oculomotor capture by allowing for the location where onset distractors are expected to appear. Observers did not explicitly indicate which items as distractors would appear in the visual search at the beginning of the trial. This only suggests that implicit memory can modulate oculomotor capture. More memory-driven automatic orienting occurs in the early stages (Berggren & Eimer, 2018; Hickey et al., 2010; Lu et al., 2017), whereas the inhibitory effect of memory content on distractors occurs at late stages (Gaspelin & Luck, 2018; Goujon et al., 2015; B. Wang & Theeuwes, 2018). However, studies providing direct evidence for the role of memory content in the time-course of oculomotor capture do not yet exist.

Pupil size is also associated with orientation (Corneil & Munoz, 2014; Wang & Munoz, 2015). Early studies have shown that pupil dilation accompanies several cognitive processes in language-comprehension or problem-solving. Pupil measures are becoming increasingly popular in cognitive research (Klingner et al., 2011). Pupil dilation has been shown to indicate interest in the content of the visual stimuli presented, which is also thought to indicate general mental activity and to correlate with task difficulty (Hess & Polt, 1964; Kahneman & Beatty, 1966). However, little is known about pupillary responses during memory processing. In a classic study using a shortterm memory task, pupil size was found to increase proportionally to the amount of information memorized and to correlate with task difficulty (Kahneman & Beatty, 1966). Recent studies have also shown that, in addition to the amount of information in memory, pupil size is associated with the accuracy of memory representation. Recent studies have shown that, in addition to information size stored in memory, pupil size also correlates with the accuracy of memory representation (Starc et al., 2017) and the ability of pupil size to serve as a predictor of recognition memory performance (Heaver & Hutton, 2011; Naber et al., 2013; Otero et al., 2011). The response of pupil size to actively remember and not remember different previews is unknown. Therefore, pupil size was used as one of the measures in this study to examine changes in pupil size caused by different memory contents during active memory and no memory processes.

1.4 RESEARCH QUESTION

In addition to its theoretical importance, understanding which factors modulate the interaction between relative salience in the visual environment and overt oculomotor capture has profound implications for the real world. There is evidence that the processes underlying memory contents may be closely linked to the processes that produce attentional bias in response to target-driven stimuli, particularly when the items searched for are from complex real-world sources (Buswell, 1935; Castelhano et al., 2009; DeAngelus & Pelz, 2009; Yarbus, 1967). A particular finding is that participants tended to view different areas of the picture when presented with different instructions, even when the same picture was presented to them. The first question, therefore, is whether memory content influences oculomotor capture in a completely automatic and unchangeable process, or a more flexible, one that allows for the involvement of cognitive control. Furthermore, when stimuli with salient features are present in visual search, whether cognitive control such as memory content modulates the effect of salience on oculomotor capture. Particularly, when attentional capture is maladaptive, in other words, contrary to the current goal.

This study aimed to explore (1) how working memory content affects the timecourse of overt selection and (2) whether memory content modulates the association between saliency and oculomotor capture. We referenced the experimental procedure of Lavie and colleagues (2005), using a modified additional singleton paradigm as a visual search task in. combination with a working memory task. In visual search, participants were instructed to search for a singleton with a specific tilted direction, the saliency of the target and distractor was unpredictably varied using color. The aim was to investigate whether memory content with the same features as stimulus saliency has an evident effect on oculomotor capture (e.g., both the working memory task and the visual search task are color dimensional). In Experiment 1, the visual search task was performed with participants remembering either a color array or a shape array or without being required to remember the array (i.e. active memory vs. no memory). To further explore the effects of dimension-specific memory content, in Experiment 2, this task was performed only when participants remembered a color array or were not required to remember the array. A no-preview condition was also added as a baseline.

The research questions of this study are here:

RQ1: How overt oculomotor selection is influenced during visual search when working memory content has and does not have the same features as physical salience.

RQ2: Whether memory content impacts the time-course of overt oculomotor selection, entirely automatic, or more can be controlled more flexibly.

RQ3: Whether active-memory can enhance oculomotor capture by physical saliency compared to no-memory.

1.5 OVERVIEW OF RESEARCH DESIGN

Our work was paired with a modification of van Zoest and Donk's (2008) additional singleton task with a working memory task. First, interference from distractors with the same features in one particular dimension (i.e., color) as memory content can be directly compared to those with different features in another dimension (i.e., shape). Second, in terms of data analysis, we attempted to plot the percentage of correct saccades landing on the target as a function of saccade latency, comparing oculomotor capture by the target between early and late selection. Moreover, pupil size was included in subsequent analyses as a factor reflecting cognitive processes, comparing the effect of different preview-memory on pupil dilation.

In the visual search task, participants were asked to search for a singleton in a specific direction and the red color defining saliency had unpredictable variation between the distractor and the target. While the remaining singletons in the display remained white. The preview of working memory was manipulated by whether the feature to be remembered in the memory display prior to the search presentation was color or shape. In the active memory condition, the working memory task required participants to remember an array of four colors (i.e. color-memory) or an array of four shapes (i.e. shape-memory). In the no-memory condition, however, no arrays were required to be remembered (i.e. no-memory).

1.6 SUMMARY

In summary, recent studies on eye movements have shown that initial saccades are guided in different ways in different time windows (e.g., van Zoest & Donk, 2006), either independently in a bottom-up manner by the stimulus or in a top-down manner by the current target (van Zoest & Donk, 2004, p. 20). However, the questions that this study sought to explore were (1) how overt oculomotor selection is influenced during visual search when working memory content has and does not have the same features as physical salience, (2) and how it changes dynamically over time. (3) Whether active memory performs differently compared to no memory for saccadic eye movements under different previews of working memory. The present study, therefore, sought to provide evidence for these issues using eye-tracking technology and experiments that combined a working memory task with an oculomotor capture task.

Chapter 1 is a comprehensive review of the literature on the effects of working memory on selective visual attention. We discuss separately some of the main topics of research findings on the effects of working memory and its content on the covert attentional selection and overt oculomotor selection, and the controversy. This clarifies how this controversy was developed further in this study. In Chapters 2 and 3, the topics discussed include the design and implementation of the experiments in Experiments 1 and 2 respectively, the methods of data analysis, and the specific details and discussion of the findings. A general overview and interpretation of the study results are then presented in Chapter 4.

CHAPTER 2 – EXPERIMENT 1

This chapter examines the relationship between working memory content and the time course of oculomotor capture by manipulating the type of working memory preview to test the hypothesis that executive memory content can play a moderating role. Based on the previous study by an Zoest and colleagues (2005), this experiment used a modified oculomotor capture task as a visual search task and paired it with a working memory task. In the working memory task, participants were asked to remember or not remember four different colors or shapes presented. After a visual search task, participants were asked to make a saccade to the position of a specifictilted target singleton, while a distractor always had an opposite orientation to the target. The saliency of stimuli was defined by color (red as salient, white as non-salient) and presented unpredictably on the target or distractor across trials. This experiment was 2 memory type (active memory vs. no-memory) × 2 memory content (color-preview vs.

shape-preview) × 2 target salience (salient-target vs. salient-distractor) withinparticipant design.

We speculate that there are at least two possible outcomes. Therefore, we presumed that there are at least two possible outcomes. It may be the case that oculomotor capture and distractor inhibition are modulated by specific visual representation in working memory (e.g., Lu et al., 2017). In this case, the hypothesis is that search items with the same feature as the memory content (color in this research) would lead to more oculomotor capture by the salient color than shape-memory and nomemory, and this effect would be more evident under active working memory. Alternatively, oculomotor capture and distractor suppression may depend on nondimensional processes and be content-specific (e.g., Lavie, 2005). In this case, we predict that working memory content should not affect the time-course of overt selection.

2.1 METHOD

2.1.1 Participants

Twenty-eight young undergraduate students, ranging in age from 19 to 23 years (M = 20.43, SD = 1.17, 19 females and 9 males) were recruited from the School of Psychology at the University of Birmingham. Informed consent was obtained from each participant before starting the experiment. The Ethical Committee of the University of Birmingham approved this study (Ethical Approval Code: 19-0034). All participants reported normal or corrected-to-normal vision and normal color vision and they were given university credits for their participation. Therefore, twenty-three participants were eligible for testing in the subsequent analysis. Five individuals were excluded because they did not complete the full trial and left midway through the trial.

2.1.2 Apparatus

Participants were seated 60 cm from a 23-inch Genenic PnP screen (100 Hz; resolution 2,048 × 1,280 pixels) in a dimly lit room. Stimulus presentation was controlled by an Intel(R) UHD Graphics 630 card. Open-sesame was used for the experimental programming (Mathôt et al., 2012), and an EyeLink 1000 plus was used to collect the eye movement data (SR Research, Ontario, Canada). The sampling frequency was set to 1000 Hz. Data on eye-movement were collected from either the right or left eye of a monocular observation. Head movements were controlled to minimise during rest by holding the participant's head on the chin rest. A five-point grid calibration procedure was completed at the beginning of the experiment, with additional calibrations added as necessary (e.g., poor recording due to contact lens or glasses reflections).

2.1.3 Stimuli

Participants were required to perform a rapid saccade to a pre-defined target in a visual search task. This saccade was only initiated after the central fixation point was offset. All stimuli were displayed on a screen with a grey backgrounded (RGB: 87,83,83). To start each trial, a fixation point appeared as a drift correction in the centre of the screen (see Figure. 2b left). All memory items were either four different colored squares or four different white shapes (see Figure. 2a). The color stimulus pool consists of six original colored squares: orange (RGB: 252,152,2), pink (RGB: 234,152,231), blue (RGB: 25,152,231), dark blue (RGB: 0, 0, 255), purple (112, 48 160) and green (RGB: 25,152,2). The shape stimulus pool consists of six white shapes: star, triangle, pentagram, heart, cross, diamond and circle.

The search array consists of 255 lines fitted in a 15 × 15 rectangular matrix. 253 non-target lines were vertical whereas the target and distractor could be tilted 45° either to the left or the right. The length of the lines was 0.57° and their width was 0.12° (see Figure. 2b, right). There is a target (a singleton tilted 45° or -45° to the vertical line), a distractor (in the opposite direction to the target), and a series of non-targets in the search array. The position of the target was actually on a square arranged in the raster, where the distance between each stimulus is 0.8° of view angle. The target and distractor were randomly presented in one of four positions. The critical 4 targets and distractor positions (one in each quadrant) are (4, 4), (12, 4), (4, 12) and (12, 12). The specific use of color-saliency divides the relationship between memory content and physical saliency into two types: a salient-target condition (a red target with a white distractor) and a salient-distractor condition (a red distractor with a white target). A target and distractor could be either red (RGB:255, 0, 0) or white (RGB: 225, 225, 225). All remaining non-targets are always white (RGB:225, 225, 225).

a. Memory Display

B. Search Display

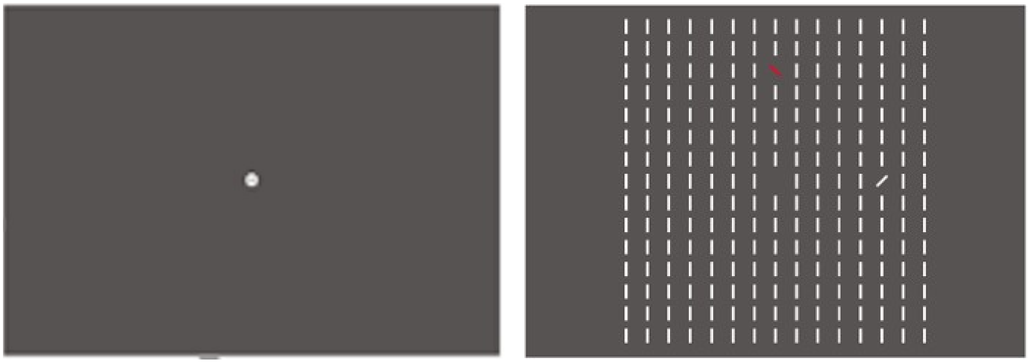

Figure 2. (a) A working memory display of an example from Experiment 1. The color array is presented with four squares of different colors (left), and the shape array is companied with four different shapes on display (right). (b) The primary stimulus is shown as an example. A search target is a line with a 45° rightward rotation and is colored white. A homogeneous set of vertical elements is called non-targets, while an additional and

unrelated 45° leftward tilted singleton is called a distractor and is colored red.

2.1.4 Design

Experiment 1 used a 2 × 2 × 2 repeated-measures within-subjects design, with memory-type (active-memory vs. no-memory), memory-content (color-preview vs. shape-preview), and target-saliency (salient-target vs. salient-distractor) as factors. The orientation of the target was informed before the experiment began and remained constant throughout the experiment, while its color changed randomly between trials (white or red). The direction and color of the distractor are always the opposite of the target. To minimise the likelihood of producing a cognitive control 'rejection template', color features of the search items consistent with the previous trial were unpredictable (e.g., Lu et al., 2017). The experiment consisted of a total of 4 conditions: color-preview memory condition, shape-preview memory condition, color-preview no-memory condition and shape-preview no-memory condition. Each participant completed 360 experimental trials and 60 practice trials. All conditions were alternated within blocks of trials. Participants performed 6 blocks of 120 trials for color-memory condition and shape-memory condition and 3 blocks of 60 trials for color-preview no-memory condition and shape-preview no-memory condition. The four preview-memory conditions occurred with the same probability on both salient-target trials (in which the target was red), and salient-distractor trials (in which the distractor was red). Firgure.3 illustrates examples of the saliency of the search item. The saliency of the target and the distractor was varied randomly within each trial. Participants were informed to rest every 60 trials. To ensure that participants understood the task correctly, both written and verbal instructions were provided.

2.1.5 Procedure

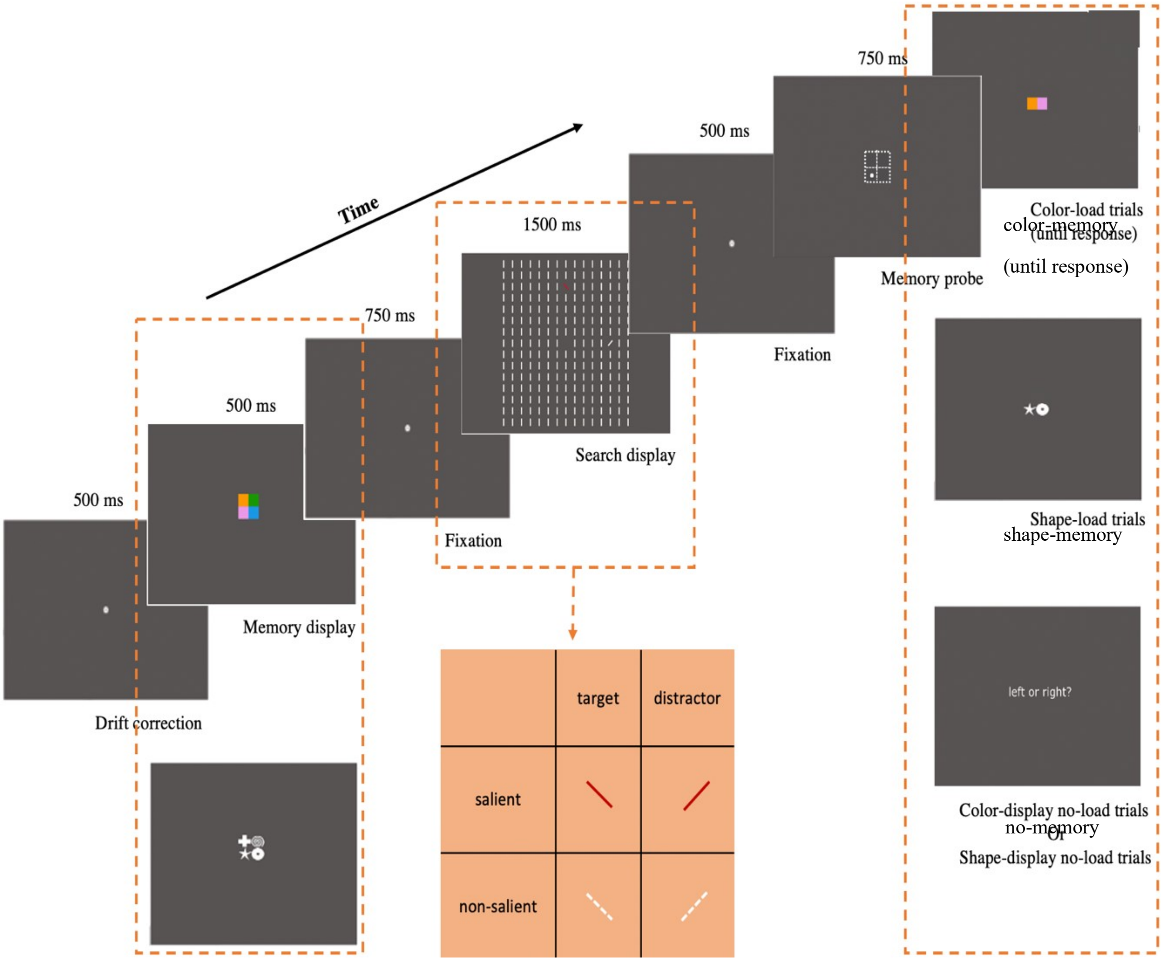

Figure 3. The trial procedure of the dual-task paradigm (not to scale). Two types of memory-content (color-preview and shape-preview) are presented in the memory array (color-memory shown in the first row in progress). There are unique tilted singletons (lefttilted target and right-tilted distractor in the example) in the search display. In this case, the target is salient (red) while the distractor is non-salient (white). A memory probe marks one of four positions. In the active-memory trials, the memory probe test gives two choices of colors or shapes for responding to which item corresponds to the remembered position, as indicated by the probe. In the no-memory condition, participants judged whether the probe occurred on the ventral midline's left or right side.

An overview of the entire experimental procedure is shown in Figure 3. A dualtask procedure was used, combining a working memory task and an additional single task (i.e., oculomotor capture task). Participants were required to start a trial by pressing the space bar to initiate a post-calibration drift. Each trial began with a fixation display for 500 ms, followed by the four memory items for 500 ms, and then the fixation display which followed 750 ms after the offset of the memory item. The memory items could be four colors selected randomly from color stimulus pool in the color-preview condition or four shapes from shape stimulus pool in the shape-preview condition. Participants were instructed to memorize the color of the shape of the memory objects and to discriminate the orientation of the target. Followed by the stimulus search was displayed for 1500 ms, participants were asked to maintain their gaze at the fixation point. In the visual search task, they were required to perform a saccade to a specific tilted target. The participants' search targets were either the right-tilted singleton or the left-tilted singleton.

After the response to the search task, there followed a memory test. Here, there is a probe dot displayed at one of the four positions previously occupied by the memory array and then two choices of color in the color-memory condition or shape in the shape-memory condition were displayed. In the active-memory condition, participants pressed the 'left' or 'right' arrows on the keyboard to indicate whether the item to the left or right of the choice matched the memory item previously presented in the marked position. In the no-memory condition, they did not have to recall memory array but just viewed the color preview in the color-preview no-memory condition or shape preview in the shape-preview no-memory condition. In order to keep the same action required for participants in the memory probe task by keypress responses as the active-memory task, and the comparable detection performance in the no-memory condition, they just had to respond to the spatial location of that probe-dot. The word 'left or right' was then presented centrally. Participants were instructed to press the key response to determine whether the probe dot had appeared on the left or right from the vertical midline of the screen using the 'left' or 'right' arrows. Feedback on the accuracy of the working memory task was provided with every 20 trials. They were informed that only accuracy would be examined in the memory task and were asked to respond as accurately and as fast as possible in the search task.

2.2 DATA ANALYSIS

The inferential and descriptive analyses were performed via STATISTICS (SPSS soft, version24) and MATLAB (The MathWorks, Version R2019a).

2.2.1 Exclusions

2.2.1.1 Behavioral Results

Incorrect responses and mean response times over three standard deviations for participants, as well as out-of-time trials, were removed from the analysis for the memory performance. The overall proportion of trials excluded from the analysis was 4.25% and 3.78% in the color-memory and shape-memory condition, respectively. A total 91.97% of trials was included in the memory performance analysis.

2.2.1.2 Eye-Movement Results

Eye movements at velocities above 80°/s (4.18%) and below 600°/s (1.6%) were defined as initial saccades. The trials excluded from the analysis also included eye movements landing at neither the target nor the distractor (3.6%) and no landing coordinates (11.2%). The trials with incorrect memory responses were also excluded (8.03%). In total, 28.61% of trials were excluded from the analysis and 71.39% of trials were included in the eye-movement analysis.

2.2.1.3 Pupil Results

According to the literature (Kret & Sjak-Shie, 2019), pupil data were excluded, filtered and smoothed. To ensure that pupil size was measured accurately, trials were discarded from the analysis when the difference in pupil size between two adjacent time points exceeded 250 mm at a sampling frequency of 1000 Hz. When a blink was detected, the pupil values before and after the blink were used for linear interpolation to replace the pupil values during the blink. Trials in which both blinks occurred within a time interval shorter than 500 ms were also removed. In both experiments, the above criteria resulted in less than 2% of the trials being discarded. Together with the trials removed from the eye movement analysis, a total of 70% of trials were eventually included in the pupil analysis. Note that, unlike the eye-movement data analysis, only pupil values during the memory display were extracted for subsequent pupil analysis (0-500 ms after the memory stimuli onset) to test the effect of memory-preview.

2.2.2 Analysis

For all causal measures investigated, error distributions were assessed, the assumption of normality was tested by using the Shapiro-Wilk normality test and the assumption of homogeneity of variance was tested by using the Levene test. Unless otherwise stated, the data confirmed this hypothesis.

2.3 RESULTS

2.3.1 Memory Performance

As shown in Fig. 4, the overall accuracy was 88.2% (SD = 14.1%), with 82.1% for the color-memory condition (SD = 13%), 75.6% for the shape-memory condition (SD = 14.6%), 97.2% for the color-preview no-memory condition (SD = 4.9%) and 98% for the shape-preview no-memory condition (SD = 4.4%).

A 2 × 2 × 2 repeated-measures ANOVA was conducted on memory accuracy with memory-content (color-preview vs. shape-preview), memory-type (active-memory vs. no-memory) and target-saliency (salient-target vs. salient-distractor) as dependent variables. The main effects were found for memory-content, $F\ (1, 22) = 7.98, p < 0.05$, $\eta^2 = 0.27$, and memory-type, $F\ (1, 22) = 47.29, p < 0.001$, $\eta^2 = 0.68$. Accuracy rates were higher for color-preview trials (mean 89.67%) than for shape-preview trials (mean

86.79%). Responses were more accurate for no-memory trials (mean 97.62%) than for active-memory trials (mean 78.84%). An interaction between memory-type and memory-content was found, $F\ (1, 22) = 20.6, p < 0.001, \eta^2 = 0.48$. The effect of memory-content on memory performance changed as a function of memory-type. Simple effect analysis further showed that memory performance was better in the colormemory condition than in the shape-memory condition, $F\ (1, 22) = 15.65, p < 0.001, \eta^2 = 0.42$. In the no-memory condition, there was no difference in memory accuracy between color-preview and shape-preview, $F\ (1, 22) = 0.96, p = 0.34, \eta^2 = 0.04$. No other effect and interaction reached significance (all *Fs* < 0.08, *ps* > 0.78).

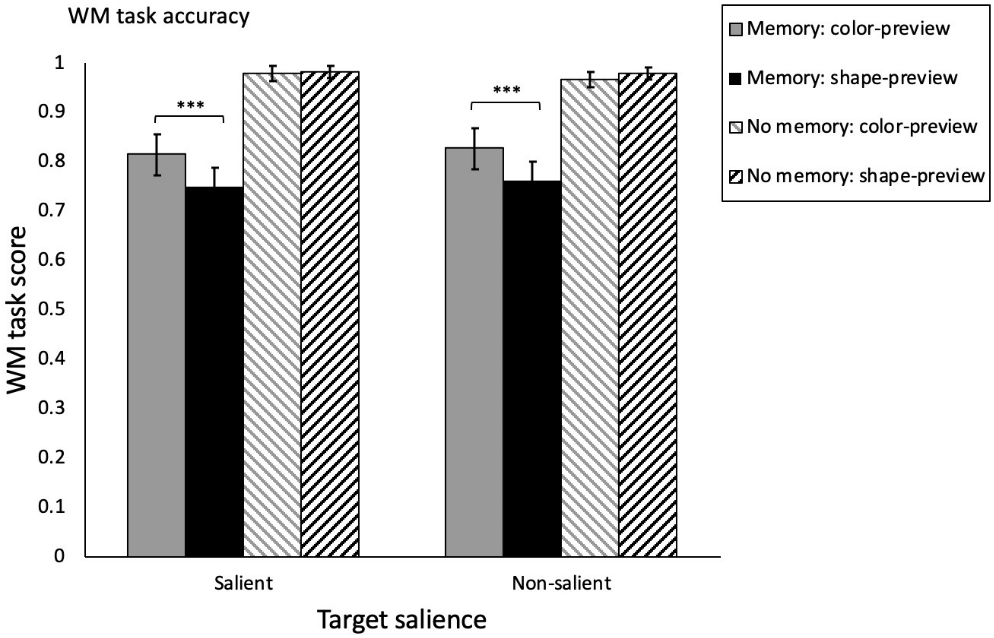

Figure 4. The results of the accuracy of memory test. *** indicates p < 0.001, and Error bars are SEM.

2.3.2 Saccadic Selection

2.3.2.1 Overall Pattern of Eye-Movement

A 2 × 2 × 2 repeated-measures ANOVA was conducted on the mean percentage of correct saccades to target, with memory-content, memory-type and target-saliency as factors. From looking at Figure 5a and 5c, it becomes clear that the relationship between memory-content and target-saliency is different in the color condition compared to the shape condition. This was confirmed by a three-way interaction among memory-type, memory-content and target-saliency, F (1, 22) = 18.08, $p < 0.001$, $\eta^2 = 0.39$. Looking specifically at the color-preview condition, there was a two-way interaction between memory-type and target-saliency F (1, 22) = 14.33, $p < 0.001$, $\eta^2 = 0.38$, while there was no such two-way interaction for the shape condition, F (1, 22) = 0.01, $p = 0.91$, $\eta^2 = 0.001$. Post-hoc follow-up comparisons showed that in the color-memory condition, there was a reliable difference between the salient target condition and the non-salient target condition ($t = 3.17$, $p = 0.047$). In the color-preview no-memory condition, there was no difference between the salient target condition and the non-salient target condition ($t = 0.14$).

Results moreover revealed that in the no-memory condition, the impact of targetsaliency was larger for the shape-preview compared to the color-preview condition, F (1, 22) = 4.79, $p = 0.039$, $\eta^2 = 0.18$. In the active-memory condition, the influence of target-saliency was larger for the color-memory condition than the shape-memory condition F (1, 22) = 7.94, $p = 0.01$, $\eta^2 = 0.27$.

No other main effect or interaction reached significant (all Fs < 3.03, ps > 0.96).

2.3.2.2 Saccade Latency

Saccade latency is defined as the time from the onset of the target to the initial of the saccade. In subsequent analyses, saccadic response times that were less than three standard deviations from the average time were not considered.

A repeated-measures ANOVA was performed on the mean saccade latency to the target, with memory-content, memory-type, target-salience as independent factors. The results revealed that main effects for memory-type, F (1, 22) = 7.34, $p < 0.05$, $\eta^2 = 0.25$, and for target-saliency, F (1, 22) = 85.86, $p < 0.001$, $\eta^2 = 0.79$ (Fig. 5c). On average, active-memory triggered slower saccades to the target (mean 266.26 ms) than nomemory (mean 249.91 ms). The average saccadic response times was longer in the salient-distractor trials (mean 279.44 ms) than in the salient-target trials (mean 236.73

ms). No main effect of preview-type, *F* (1, 22) = 1.75, p = 0.2, η^2= 0.07. No other interaction reached significance (all *Fs* < 1.34, *ps* > 0.26).

A similar repeated-measures ANOVA was conducted on the mean saccade latency to the distractor. The main effects of memory-type, *F* (1, 22) = 11.78, $p < 0.01$, η^2= 0.35, and target-saliency, *F* (1, 22) = 70.79, $p < 0.001$, η^2= 0.76, were found (Fig. 5d). Active memory elicited slower saccades to the distractor (mean 275.81 ms) than no memory (mean 251.47 ms). In the salient-target trials, the mean saccadic response (mean 285.41 ms) was slower than in the salient-distractor trials (mean 241.87 ms). No other main effect or interaction was found (all *Fs* <1.68, *ps* < 0.78).

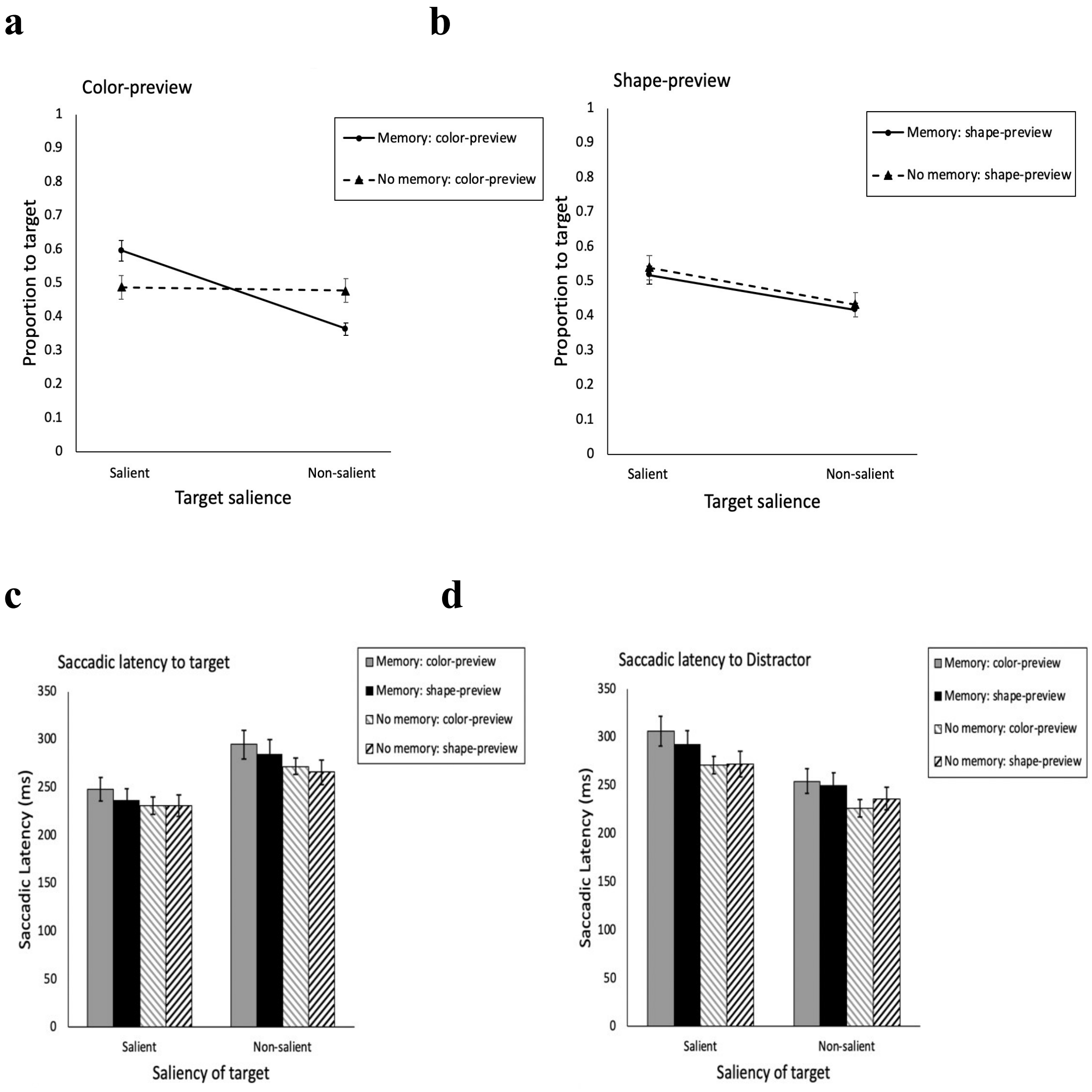

Figure 5. The overall percentage of correct to either salient target or non-salient target as a function of memory type in the color-preview condition (a) and in the shape-preview condition (b). The overall oculomotor responses of saccades to the target (c) and the distractor (d) as a function of the target-saliency. Error bars are SEM.

2.3.2.3 Time-course of Selection

To determine how eye movements were triggered and when they occurred, the distribution of performance as a function of initial saccade accuracy across the eight conditions was analysed and plotted (see Fig. 6 a-d). For four conditions (color-memory vs. shape-memory vs. color-preview no-memory vs. shape-preview no-memory) and two saliency type (salient-target vs. salient-distractor), individual distributions of initial saccade latencies were calculated for each participant regardless of the saccadic destination. The distribution was calculated for each bin based on the proportion of correct saccade towards the target and saccade latency thus was divided into bins (4). The mean saccade latency was calculated for each bin.

In order to figure out how saccade performance changed as a function of time, a repeated-measures ANOVA was conducted. Bin was only seen to interact with targetsalience, F (1, 22) = 122.02, $p < 0.001$, $\eta^2 = 0.85$. Simple effect analysis further showed that in the first bin, more correct saccades were directed to the salient target (mean 76.2%) than the non-salient target (mean 22.7%), F (1, 22) = 121.11, $p < 0.001$, $\eta^2 = 0.85$. In contrast, in the last bin, more correct saccades were directed to non-salient targets (mean 59%) than to salient targets (mean 34.5%), F (1, 22) = 59.12, $p < 0.001$, $\eta^2 = 0.73$. The four-way interaction was not significant, F (1, 22) = 0.069, $p = 0.79$, $\eta^2 = 0.003$. No other main effect and interaction reached significance (all *Fs* < 1.19, *ps* > 0.29).

From Figure 6a and 6c, there was an evident difference between salient-target and salient-distractor condition in the last bin for the color condition. To test this main difference, the post-hoc follow up comparisons were adopted in the first bin and last bin, separately. The results showed that in the first bin, saccades were significantly attracted toward the salient target than the non-salient target in all of the conditions (all *ps* < 0.001). In the fourth bin, while more saccades were directed to the non-salient target than the salient target in the color-preview no-memory condition (salient and non-salient: 32.09% and 65.3%; *t* = 4.78, *p* < 0.001), no such difference was found in the color-memory condition (40.52% and 54.26%; *t* = 0.69, *p* = 0.52).

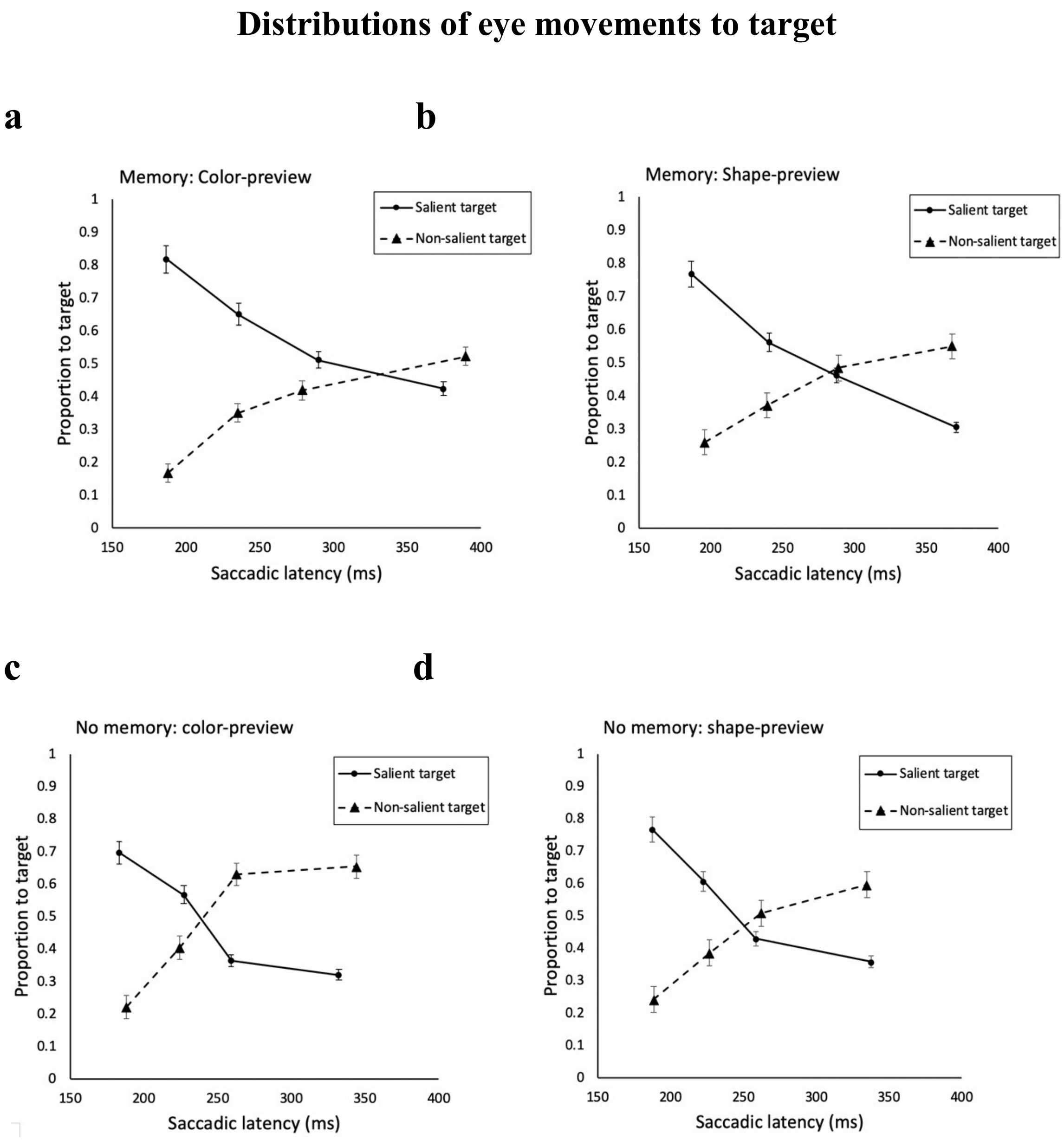

Figure 6. The overall distribution of correct saccades to the salient and non-salient target as a function of saccade latency in the color-memory condition (a), in the shape-memory

condition (b), in the color-preview no-memory condition (c) and in the shape-preview nomemory condition (d). Error bars are SEM.

2.3.3 Pupil Response

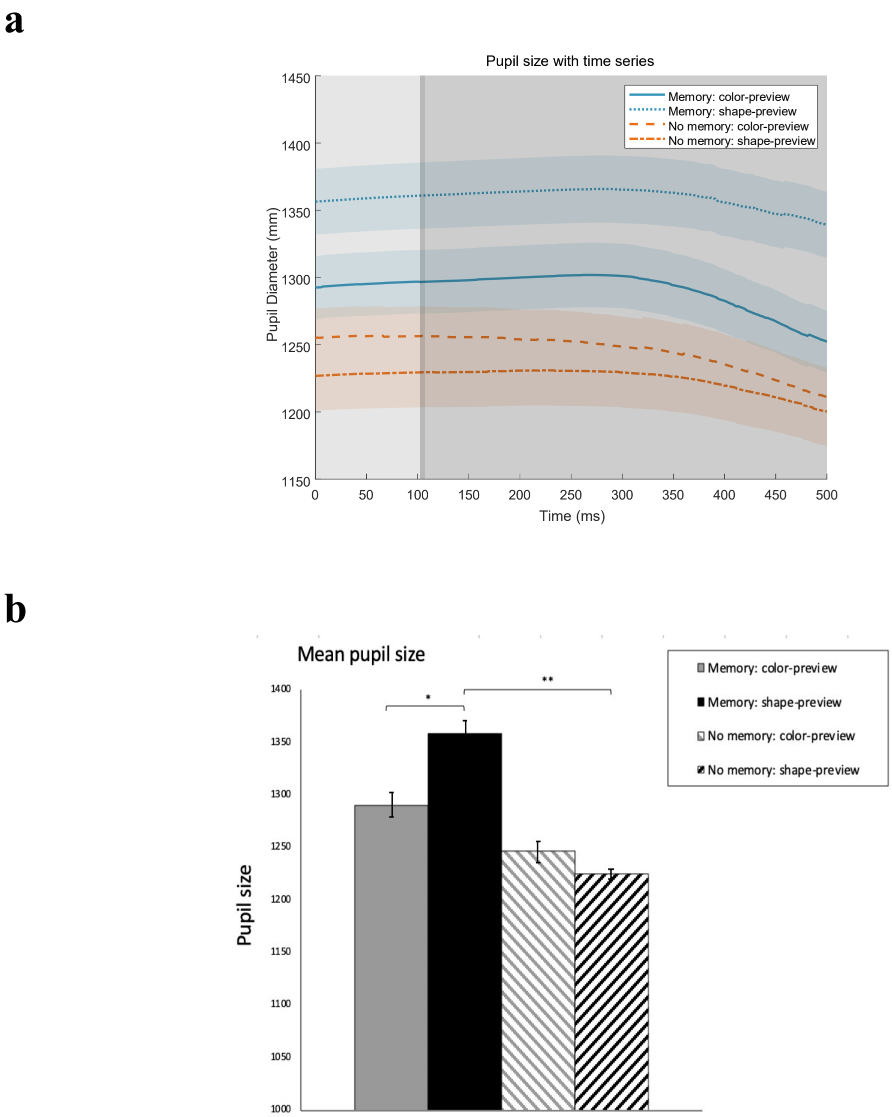

Figure 7. Change in pupillary diameter during presentation of each memory array in the four conditions (a). Mean pupil diameter in the four conditions (b). In Fig. 7a, the shaded areas around the pupil response indicate the range of ± standard errors (across participants). A dark shaded background indicates 0.01 < p < 0.05 and the light shaded

background represents $p < 0.01$. In Fig. 7b, error bars indicate ± standard error across participants. * denotes $p < 0.05$. ** denotes $p < 0.01$.

For each trial, the value of the baseline was determined by averaging the pupil size from the appearance presented in the memory array, following the baseline pupil correction procedure (Kret & Sjak-Shie, 2019). Pupil size was subtracted from this value at baseline. This study hypothesised that memory content and memory type are important for all components involved in the orientation of initiation and the saccade responses in many tasks. Therefore, the period of the working memory task, that is the 0-500 ms time after memory stimulus presentation was selected to capture continuous pupil responses.

Fig. 7a shows pupil dynamics during working memory presentation, illustrating initial pupil dilation after color-preview or shape-preview in the active-memory and nomemory conditions. After the onset of the memory stimulus, there was a significant difference in dynamic pupil size between the shape-memory condition and shapepreview no-memory condition. A series of independent-sample t-tests on pupil size were conducted for the shape-memory and shape-preview no-memory conditions, shape-memory and color-memory conditions, color-memory and color-preview nomemory conditions, and shape-preview no-memory and color-preview no-memory conditions at each millisecond point in time, respectively. A difference between the shape-memory and shape-preview no-memory conditions was found for each time point (for 0-100 ms and at 102 ms, $0.01 < p < 0.05$; at 101ms and for 103-500 ms, $p < 0.01$). A significant difference was also found between the shape-memory condition and the color-memory conditions (0-500 ms, $0.01 < p < 0.05$). There was no evident difference between the color-memory and color-preview no-memory conditions at any time point.

On average, pupil sizes were 1.290 mm, 1.359 mm, 1.246 mm and 1.224 mm in the color-memory, shape-memory, color-preview no-memory and shape-preview nomemory conditions, respectively (see Fig. 7b). An ANOVA was performed on the mean pupil size, with preview-memory (color-memory vs. color-preview no-memory vs. shape-memory vs. shape-preview no-memory) as a factor. The preview-memory had an effect on pupil size, $F(3, 20) = 3.74, p < 0.05, \eta^2 = 0.36$. The results of post-hoc test showed that the mean pupil size was greatly larger in the shape-memory condition (mean 1.359 mm) than the color-memory (mean 1.290 mm), $p < 0.05$, and shapepreview no-memory conditions (mean 1.224 mm), $p < 0.01$.

2.4 DISCUSSION

This study examined how memory-content affected dynamic overt oculomotor capture in a visual environment where irrelevant saliency matched or mismatched with memory. Participants were asked to search for specific-tilted targets in a visual search task containing salient targets or salient distractors while manipulating working memory content based on color-preview or shape-preview. Experiment 1 had three main findings.

First, stimulus-saliency greatly impacted eye-movement target selection, and the effect of working memory on salience was content-specific, as shown by the significant three-way interaction among memory-content, memory-type and target-salience. From the overall pattern of saccade-to-target, the physical saliency interfered more with oculomotor capture, as was observed with increased saccades to salient items. Such salience-elicited saccades can be enhanced by active working memory (De Houwer et al., 2017; Forester et al., 2019; Olivers et al., 2011; Palangi et al., 2016). Interestingly, we found that such an increased salience-driven effect could only be observed based on the particular preview. Specifically, remembering color information directed more saccades to salient items than non-salient items even if the salient item was sometimes task-irrelevant. Also, this saccade to saliency increased more when keeping the color in memory compared to viewing the color-preview. This also reflects that cognitive control matters automatically in oculomotor selection (Han & Kim, 2009). However, memorizing shape information without the same features as saliency did not have evident saliency-driven saccades.

Thus, such salience-driven saccades increased by active memory was contentspecific. This depended on whether the memory content overlapped with the salience of search stimuli. Remembering color information elicited more saccades toward salient items than remembering shape information, indicating that memory-content plays an important role in oculomotor capture. The most striking finding is that the difference in saccade-to-target between salient-target and salient-distractor conditions as a function of memory-type was greatly larger after color-preview. Specifically, colormemory guided more saccades toward the target in salient-target trials and more saccades toward the distractor in salient-distractor trials, suggesting salience-driven selection. In contrast, in the color-preview no-memory condition, the likelihood of oculomotor capture by color-salience was significantly lower, suggesting goal-directed control. These findings demonstrate the effect of memory-content on oculomotor capture by memory-matching salience (Soto et al., 2008). However, after the shapepreview, active-memory did not enhance oculomotor capture by salience. These results suggest that active-memory only enhanced interference from physical salience when stimulus salience was memory-matching. This is a novel finding of the present study.

The effect of memory-content on overt selection was demonstrated, suggesting that executive-control process seems to be capable of modulating oculomotor capture based on the relationship between search stimuli and memory items. The relevant previous studies (e.g., Awh et al., 1998; O'Craven et al., 1999; Pashler & Shiu, 1999) also indicated that memory-content gives memory-matching stimuli more advantage in an automatic manner, such as attentional selection biased toward irrelevant but memory-matching stimuli. In addition, shape-memory directed fewer saccades to salient targets but more to non-salient targets compared to color-memory. This finding supports the idea that memory-matching stimuli are less likely to attract overt attention when memory information and search stimuli are of different modalities (e.g., Kim et al., 2005). Note that for the longest saccade latency, the difference between the salienttarget and non-salient target was greatly larger as a function of memory-type, only for the color-preview. While the salience-drive oculomotor capture was observed in the shortest latency, viewing the color-preview showed the evident inhibition of colorsalience. However, color-memory did not show such inhibition.

Second, we found a remarkable effect of stimulus saliency on dynamic oculomotor selection due to the interaction between target-saliency and bin. While more saccades preferred salient items, supporting that task-irrelevant saliency can capture overt oculomotor in a bottom-up way (Sander et al., 2011; van Zoest & Donk, 2004, 2005; Steven Yantis & Hillstrom, 1994), saliency did not always capture the saccade. The saliency-driven effect was more evident when the interval between target onset and initial saccade was short (i.e., early stages), but goal-directed control was stronger at later times. This finding supports the idea that goal-directed control and stimuluselicited selection independently contribute to oculomotor selection at different time points (van Zoest & Donk, 2004, 2005). This appears to be an early involuntary process driven by stimulus salience and a more goal-driven control process later (Cheal & Chastain, 2002; Ludwig & Gilchrist, 2002; Müller & Rabbitt, 1989). However, there was no significant interaction between the bin and working memory, suggesting that while performance to the salient target and non-salient target dramatically varied as a function of time, the memory-content and memory-type condition did not further modulate these dynamics.

Third, we found that the behavioural responses in Experiment 1 were inconsistent with overall oculomotor performance and this effect of active-memory appeared to be content-specific for overt oculomotor selection. While saccade accuracy was better after the shape-preview, memory performance was better after color-preview. This controversy may be due to the fact that memorizing four different shapes is more difficult than memorizing four colors. Both dynamic and average pupil responses between the color-memory and shape-memory conditions also support this interpretation. Pupil size was much larger when remembering the shape-preview relative to remembering the color-preview, suggesting that the task-difficulty of the shape-memory condition was greatly higher and therefore requires more cognitive resources. Recent studies have also shown that pupil size only reflects the processing load (Meghanathan et al., 2015). This could also partially explain that there is no significant pupil dilation for color-memory, due to the low cognitive resources required to remember colors and the low processing load. Thus, we proposed that although memorizing shape information is more complex and taxes more cognitive resources relative to color information, it has no effect on visual selection - a result that argues against the idea that working memory taxes executive control in a general way (Lavie & De Fockert, 2005).

Overall, this chapter is about Experiment 1, which provides evidence for the effect of working memory content on overt selection based on the relationship between memory and search item features. First, a significant difference in initial saccades between salient-target and non-salient target conditions was greatly large after the color-preview. Color-memory elicited more oculomotor capture by color-saliency, whereas when viewing the color-preview without memory, more saccades were directed to non-salient targets and improved search performance. However, there was no such difference for the shape conditions. Thus, working memory enhanced the interference from salience only when it matched to memory-content. Second, stimulus saliency had an evident effect on the time-course of overt oculomotor selection, but working memory had no effect on the dynamic saccade. This supports the idea that more saliency-driven automatic oculomotor capture in the early stages and more strategic goal-directed control in the later stages. The two processes operated independently at different time windows. Third, behavioral data is not fully consistent with eye-movement data. While memorizing the shape-preview performed better in saccade selection, memorizing the color-preview performed better in the memory probe test. And the pupil size during remembering the shape-preview was larger than the color-preview. This suggests that the task-difficulty of the shape-memory task was higher and this also against the idea that working memory taxes executive control in a general way.

The interesting finding in the present study is that the difference between the salient-target and non-salient target conditions as a function of memory-type was greatly larger, only when there was an overlap in the features between the preview and stimuli features signalling stimulus-salience, i.e., in the color-preview condition. Compared with no-memory, active color memory caused more saccades to colorsalience even if the salient item was task-irrelevant, suggesting saliency-driven selection. In turn, when viewing the color-preview, more saccades were directed to nonsalient targets, suggesting goal-directed control in the former. However, this difference as a function of memory-type was not apparent in the shape-preview condition. In addition, there is an inhibition of irrelevant color information in the longest saccade latency only in the color-preview no-memory condition, revealing a benefit for the salient-distractor condition. Compared to previous work showing without using the preview condition (van Zoest & Donk, 2005), the extent of saliency inhibition was substantially greater measuring over 30% benefit in the performance of the salientdistractor condition compared to the intuitively easier salient-target condition (see Fig. 6c). However, there was less salience inhibition in the color-memory condition. Based on this, we speculated that priming observers with a color-preview before the search display may probe them to inhibit color more generally and thus produce a strong inhibition later during overt oculomotor selection. Experiment 2 was conducted to test this hypothesis.

We tested these findings by focusing only on the effect of the color-preview with the same features as stimulus saliency on overt selection and then compared the results directly with Experiment 1. The next chapter 3 will further investigate how the colorpreview affects overt selection and whether active-memory can enhance oculomotor capture by salience while no-memory can reduce the interference from salience.

CHAPTER 3 – EXPERIMENT 2

A striking finding was obtained in Experiment 1, where active memory for color information showed stronger saliency-driven selection when the memory-content was the same as search saliency. In contrast, just viewing the color-preview reflected inhibition of saliency later during overt selection (i.e., in favour of salient-distractor condition). This benefit was even more than viewing no-preview (e.g., van Zoest & Donk, 2005). Thus, to further investigate whether the color-preview that overlapped with search stimuli salience could affect saccadic selection as a function of memorytype, the second experiment was designed. Experiment 1 demonstrated that activememory enhanced saliency processing only when the features signalling salience was overlapped to that of the memory-content. Thus, Experiment 2 used the color information and no information as the preview before the search display with the aims of (1) replicating the findings of Experiment 1 and (2) further investigating the effect of the color-preview as a function of memory-type. The color-memory condition and the color-preview no-memory condition was presented in the same way as in Experiment 1, but an additional no-preview no-memory condition was added. There were four blank squares in the no-preview no-memory condition as a control condition. Given the results in Experiment 1, the hypothesis was proposed that memorizing the color-preview would enhance more saliency processing. However, viewing the colorpreview would show more goal-directed control and reduce oculomotor capture by salience, relative to the control condition that did not present the color preview. This benefit in the salient-distractor condition maybe even better than when viewing the nopreview.

3.1 METHOD

3.1.1 Participants

Thirty young undergraduate students aged 19-23 years (M = 20.85, SD = 1.19, 22 females and 8 males) were recruited from the School of Psychology at the University of Birmingham to complete the experiment in the Visual and Motor Laboratory. Informed consent was obtained from each participant before the experiment and the Ethical Committee of the University of Birmingham approved the study (Ethical Approval Code: 19-0034). All participants reported normal or corrected-to-normal vision and normal color vision and they were given university credit for their participation. To ensure Experiment 2 had the same adequate statistical power as Experiment 1, we used the amount of variability in the outcome that is accounted for by the three-way interaction among memory-content, memory-type and target-salience in Experiment 1. The partial Eta squared ($\eta p^2 = .39$) was adopted to calculate the validity effect size using G-power software. A minimum sample size of 10 participants achieves the expected statistical power of a validity effect of .99 when corrected for publication bias (de Fockert, 2013). Thus, in Experiment 2, after excluding 5 participants due to the incomplete trials, our sample of 25 (more than 10) was suitable for testing this effect.

3.1.2 Stimuli

As in Experiment 1, stimuli were presented on a screen with a grey background (RGB: 87,83,83). All memory items consisted of four colored squares in the colorpreview condition, or four blank squares as a baseline in the no-preview condition (see Figure. 8). The color stimulus pool consisted of 6 original colored squares: orange (RGB: 252,152,2), pink (RGB: 234,152,231), blue (RGB: 25,152,231), dark blue (RGB: 0, 0, 255), purple (112, 48 160) and green (RGB: 25,152,2); the baseline stimulus pool consisted of four blank squares.

Memory Display

Figure 8. An example of the working memory display in Experiment 2. The color array is presented with four squares of different colors (left), and the no-preview condition is companied with four blank squares on display (right).

3.1.3 Design

Experiment 2 used a 3 × 2 repeated-measures within-subject design with the preview-memory type (color-memory vs. color-preview no-memory vs. no-preview no-memory) and target-saliency (salient-target vs. salient-distractor) as factors. Similar to Experiment 1, the color and orientation of the target were always the opposite of the distractor in Experiment 2. The search array consists of 255 lines fitted in a 15 × 15 rectangular matrix. 253 non-target lines were vertical whereas the target and distractor could be tilted 45° either to the left or the right. The possible position of the target was actually on a square arranged in this raster, with a distance of 8° from each stimulus. Target and distractor were randomly presented in one of four positions. The critical target and distractor positions (4, one in each quadrant): positions = [(4, 4), (12, 4), (4, 12), (12, 12)]. The color feature of the target and the distractor were unpredictable between trials to minimise the likelihood of producing a cognitive control 'rejection template' (e.g., Lu, 2017). Participants completed blocks of 60 trials for each condition in random order. There were 18 blocks of 360 experimental trials and 3 blocks of 60 practice trials. Each condition consisted of 120 trials.

3.1.4 Procedure

There were three conditions: the color-memory condition, the color-preview nomemory condition and the no-preview no-memory condition. The experimental procedures for the color-memory and color-preview no-memory conditions were the same as in Experiment 1. In the no-preview no-memory condition, participants were required to view four white squares without working memory. This condition was referred to as the control condition, comparing overt performance with the colorpreview condition. The same instructions were provided. In the working memory task, participants were asked to memorize color information in the color-memory condition and viewing the color-preview without remembering anything in the color-preview nomemory condition and viewing without preview in the no-preview no-memory condition. The visual search task required participants to saccade the target, followed by the memory probe test, which required selection by fast and accurate key presses. In the color-memory condition, two-color choices were presented centrally. Participants were indicated whether the item positioned to the left or right matched memorized color presented at the position marked by the probe. They responded using the 'left' or 'right' arrow on the keyboard. They did not have to remember the memory array in the nomemory condition. But they still viewed the color-preview in the color-preview nomemory condition and the no-preview in the no-preview no-memory condition. In order to be consistent with the operation required for the memory condition, they were asked to respond to the spatial location of that probe. The words 'left or right' were presented centrally, instructing participants to respond to the probe occurring left or right from the vertical midline of the screen using the 'left' or 'right' arrow. Feedback on the accuracy of the working memory task was provided once every 20 trials.

3.2 DATA ANALYSIS

Inferential and descriptive analyses were performed by STATISTICS (SPSS soft, version24) and MATLAB (The MathWorks, Version R2019a). All dependent measures and exclusions for memory performances, saccadic eye movements, and pupil results were the same as in Experiment 1.

3.2.1 Exclusions

3.2.1.1 Behavioral Results

Similar to the exclusion criteria used in Experiment 1, we discarded trials from the analysis for memory performance, including incorrect responses and mean response times for participants with more than three standard deviations, as well as out-of-time trials in Experiment 2. The total percentage of excluded trials was 3.33% in the colormemory condition, 0.83% in the color-preview no-memory condition and 0.02% in the no-preview no-memory condition. A total of 95.82% of trials were included in the analysis of memory performance.

3.2.1.2 Eye Movements Results

As with the criteria used in Experiment 1, eye movements with velocities above 80°/s and below 600°/s were defined as initial saccades. Trials that failed to meet these criteria were excluded from the analysis (5.18%). Saccades excluded from the analysis also included eye movements that were pointed neither to the target nor to the distractor (1.5%) and no landing coordinates (8.4%). Furthermore, we included only saccades performed on trials where correct memory responses were obtained (4.48%). In total, 80.44% of trials were included in the eye-movement analysis.

3.2.1.3 Pupil Results

As the procedure done in Experiment 1, following the baseline pupil correction procedure (Kret & Sjak-Shie, 2019), a baseline value was calculated by averaging the pupil diameter of each trial that occurred during the memory array presentation. The pupil diameter was subtracted from this value at baseline. As mentioned in Experiment 1, only the period of the working memory task (a time period of 0-500 ms after the presentation of the memory stimulus) was selected to capture the continuous pupil response. In the pupil analysis, less than 2% of the trials were discarded by the baseline pupil correction procedure, as well as 19.56% of the trials that did not meet the criteria for saccade analysis. Thus, a total of 78.44% of the trials were included in the pupil analysis.

3.3 RESULTS

3.3.1 Memory Performance

Memory accuracy was first measured in the memory probe test (see Figure. 9). After color-preview, the memory accuracy was 83% (SD = 13.14%) and 98.69% (SD = 1.81%) in the color-memory and color-preview no-memory conditions, respectively. In the no-preview no-memory condition, the accuracy result was 98.32% (SD = 2.38%).

A 3 × 2 repeated-measures ANOVA was conducted with preview-memory type (color-memory vs. color-preview no-memory vs. no-preview no-memory) and targetsaliency (salient-target vs. salient-distractor) as within-subject variables. A significant main effect of preview-memory type was found, $F\,(2, 23) = 23.96, p < 0.001$, $\eta\,^2 = 0.6$. This indicated that remembering color information significantly impacted memory performance (mean 83%) compared to the color-preview no-memory (mean 98.7%) and the no-preview no-memory conditions (mean 98.3%). No other main effect and interaction was significant (all $Fs < 0.57$, $ps > 0.57$).

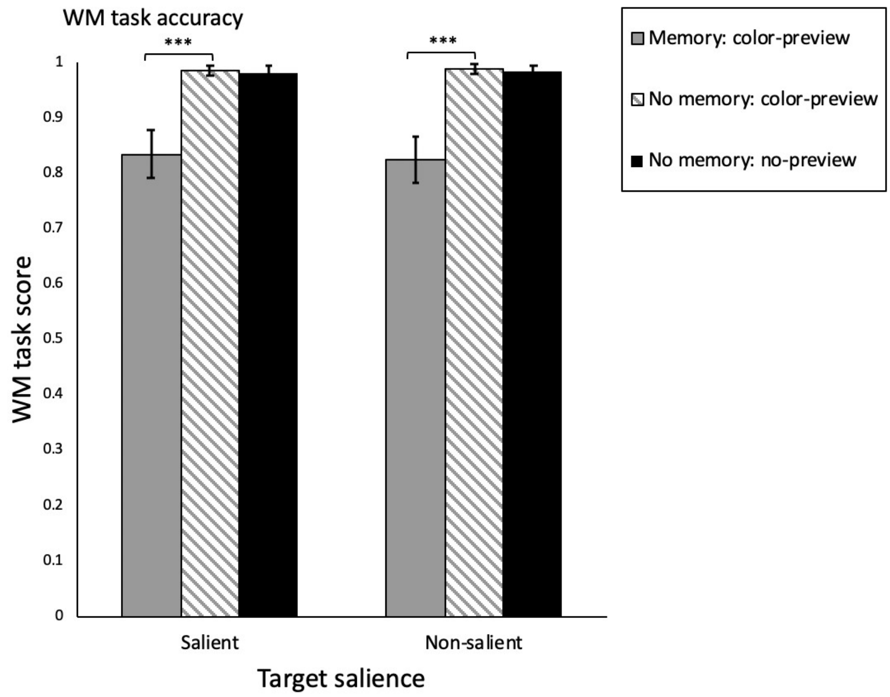

Figure 9. The results of the accuracy of the memory probe test. Error bars are SEM. *** represents p < 0.001.

3.3.2 Saccadic Selection

3.3.2.1 Overall Pattern of Eye Movements

As shown in Figure. 10a, there were the mean percentage of correct eye movements to the target in the three conditions. A 3 (preview-memory type) × 2 (targetsaliency) repeated-measures ANOVA showed no main effect of preview-memory, F (2, 23) = 0.36, p = 0.7, η^2= 0.03. A main effect of target-saliency was significant, F (1, 24) = 43.44, $p < 0.001$, η^2= 0.64, indicating that more saccades were guided toward salient targets (mean 61.9%) than non-salient targets (mean 35%). There was no interaction, F (2, 23) = 3.27, p = 0.056, η^2= 0.22.

To compare the results of Experiment 2 to Experiment 1, an ANOVA was conducted with the preview-memory type of color conditions that were shared across experiments (color-memory vs. color-preview no-memory) and target-saliency (salienttarget vs. salient-distractor) as within-subject factors and Experiment (1 vs. 2) as between-subject factors. The results showed no reliable three-way interaction, F (1,

46) = 2.38, $p = 0.129$, $\eta^2 = 0.049$, suggesting that the two-way interaction between type of preview-memory (active-memory, vs no-memory) was similar in both Experiments. The two-way interaction with preview-memory and target-saliency in Experiment 2 while ignoring the no-preview condition, was reliable, F (1, 24) = 4.63, $p = 0.042$, $\eta^2 =$ 0.16. This suggests that similar to Experiment 1, the influence of stimulus-salience in the color-preview no-memory condition in Experiment 2 was significantly reduced compared to the color-memory condition.

There was no reliable interaction as a function of target-saliency between the color-memory condition and the no-preview no-memory condition, F (1, 24) = 0.34, $p = 0.56$, $\eta^2 = 0.14$, suggesting that relative to the no-preview condition, the colormemory did not increase the effect of irrelevant stimulus-saliency. A reliable interaction as a function of target-saliency between the color-preview no-memory and the nopreview no-memory conditions was found, F (1, 24) = 4.60, $p = 0.042$, $\eta^2 = 0.16$. This indicates that more non-salient targets were selected for the color-preview than the nopreview.

3.3.2.2 Saccade Latency

A repeated-measures ANOVA was conducted on individuals' saccade latency to target, with preview-memory type and target-saliency as factors. The main effects were found for preview-memory type, F (2, 23) = 10.67, $p < 0.01$, $\eta^2 = 0.48$, and targetsalience, F (1, 24) = 157.51, $p < 0.001$, $\eta^2 = 0.87$ (see Figure.10b). The overall saccade latency to targets was slightly slower in salient-distractor trials (mean 265.72 ms) than in salient-target trials (mean 220.14 ms). Longer saccade latencies were shown when remembering colors (mean 264.42 ms) than when viewing the color-preview (mean 231.57 ms) and when seeing nothing (mean 232.79 ms). The interaction between preview-memory type and target-salience was significant, F (2, 23) = 7.36, $p < 0.01$, $\eta^2 = 0.39$. The effect of preview-memory type on saccade latency changed significantly as a function of target-saliency. Simple effect analysis showed that memorizing the color-preview caused slower eye movements to both salient or non-salient target (mean 234.24 and 294.6 ms, respectively) than viewing the color-preview and the no-preview (mean 215.61 ms and 247.53 ms), F (2, 23) = 6.98, $p < 0.01$, $\eta^2 = 0.38$.

The same ANOVA was performed on the saccade latencies to the distractors. The main effects of preview-memory type, *F* (2, 23) = 5.52, $p < 0.05$, $\eta^2 = 0.32$, and targetsalience, *F* (1, 24) = 85.45, $p < 0.001$, $\eta^2 = 0.78$, were found (see Fig.10c). When participants were asked to remember the color-preview (mean 263.6 ms), the overall saccade latency to the distractor was slower than when they viewed only the colorpreview (mean 238.03 ms) and no-preview (mean 239.69 ms). In addition, saccadic responses to distractors were slower on salient-targets trials (mean 266.42 ms) than salient-distractor trials (mean 227.79 ms). A similar interaction was found between preview-memory type and target-saliency, *F* (2, 23) = 10.97, $p < 0.001$, $\eta^2 = 0.49$.

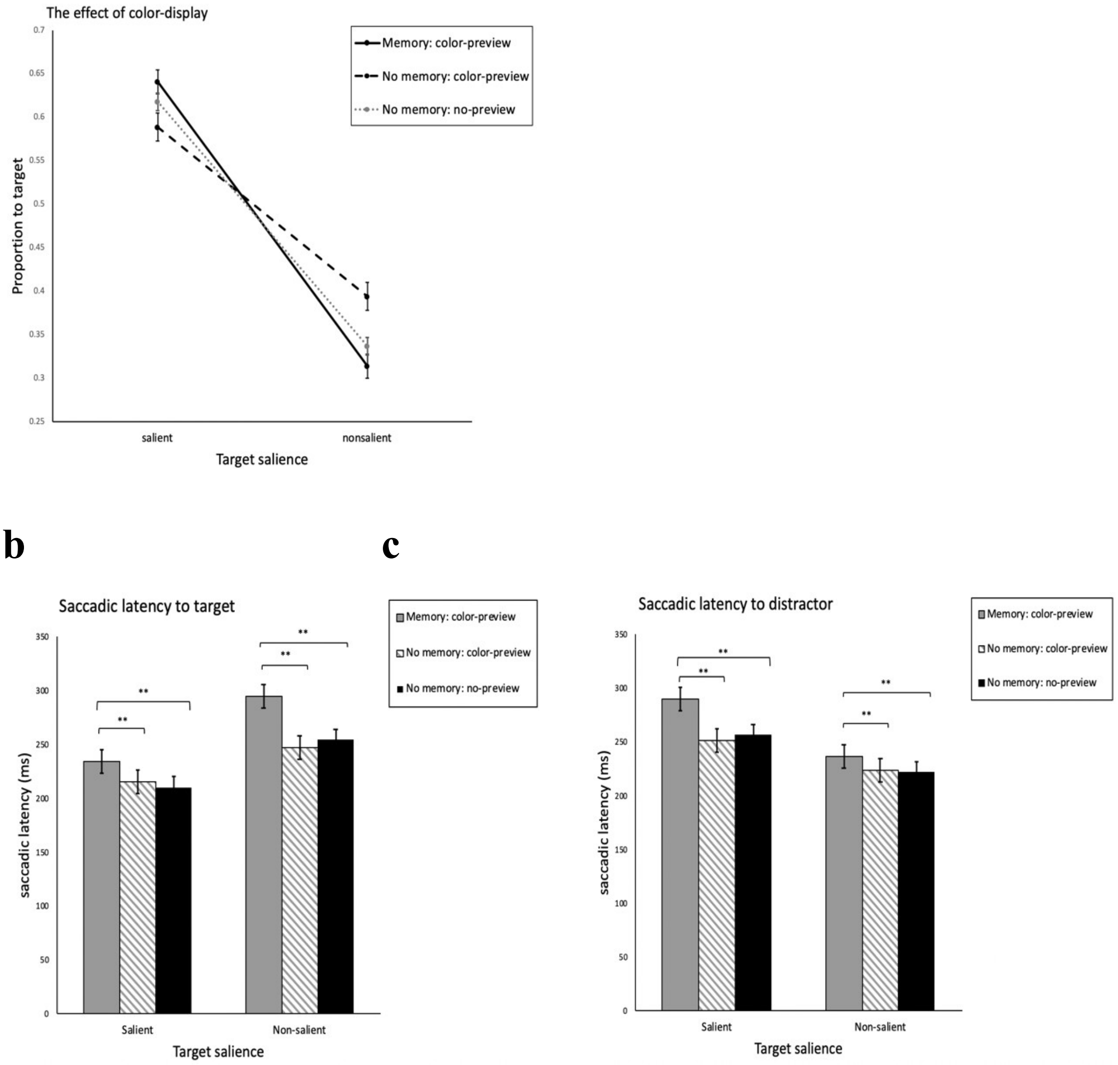

Figure 10. The overall percentage of correct saccade to the salient target and non-salient target as a function of working memory type in the color-memory, color-preview no-memory

and no-preview no-memory conditions (a). The overall oculomotor responses of saccades to targets (b) and to distractors (c) as a function of target-saliency. Error bas are SEM.

3.3.2.3 Time-course of Selection

Figure. 11a-c show the distribution of the correct proportion of saccade-to-target as a function of saccade latency in each condition, looking at the dynamics of oculomotor capture. As in Experiment 1, the individual distribution of initial saccade latencies for each participant was determined regardless of the destination of saccades for the six conditions. The distribution was divided into bins (4) according to the saccade latency, and then the correct percentage of saccade-to-target was calculated for each bin. To determine the absolute longest and shortest saccade latencies, only the first and fourth bins, referred to as the early and late visual search stages, were involved.

To figure out the change in saccade performance as a function of time, a repeatedmeasures ANOVA was performed on the correct proportion of saccade-to-target, with the preview-memory type (color-memory, color-preview no-memory and no-preview no-memory), target-salience (salient-target and salient-distractor) and bin (1 and 4) as independent factors. The main effect of bin reached significant, $F\ (1, 24) = 4.89$, $p < 0.05$, $\eta^2 = 0.17$. The more correct saccadic performance was obtained in the fourth bin (mean 50.7%) than the first bin (mean 46.7%).

A two-way interaction was found between target-salience and bin, $F\ (1, 24) = 233.89$, $p < 0.001$, $\eta^2 = 0.91$. This suggested that the effect of target-saliency changed significantly as a function of time. A simple analysis showed that for the shortest latency (i.e. first bin), more oculomotor capture by salient targets (mean 84.5%) was observed relative to non-salient targets (mean 16.9%), $F\ (1, 24) = 290.49$, $p < 0.001$, $\eta^2 = 0.92$. In turn, for the longest saccade latency (i.e. fourth bin), compared with salient targets (mean 41.7%), more saccades were directed toward non-salient targets (mean 51.6%), $F\ (1, 24) = 2.29$, $p < 0.05$, $\eta^2 = 0.23$. No other main effect and interaction was significant (all $Fs < 0.29$, $ps > 0.85$).

The post-hoc follow up test was used to focus on the main difference between the salient target and non-salient target under each condition. In bin 1, more saccades were directed toward the salient target than the non-salient target for each of the three conditions (all *ps* < 0.001). In the fourth bin, while there were more saccades directed toward the non-salient target than the salient target in the color-preview no-memory condition (non-salient and salient: 54.96% and 38.56%; $t = 3.36$, $p = 0.01$), no such difference was observed for the color-memory (47.76% and 43.80%; $t = 2.42$, $p = 0.97$) and no-preview no-memory (52.12% and 42.87%; $t = 0.26$, $p = 0.40$).

Distributions of eye movements to target

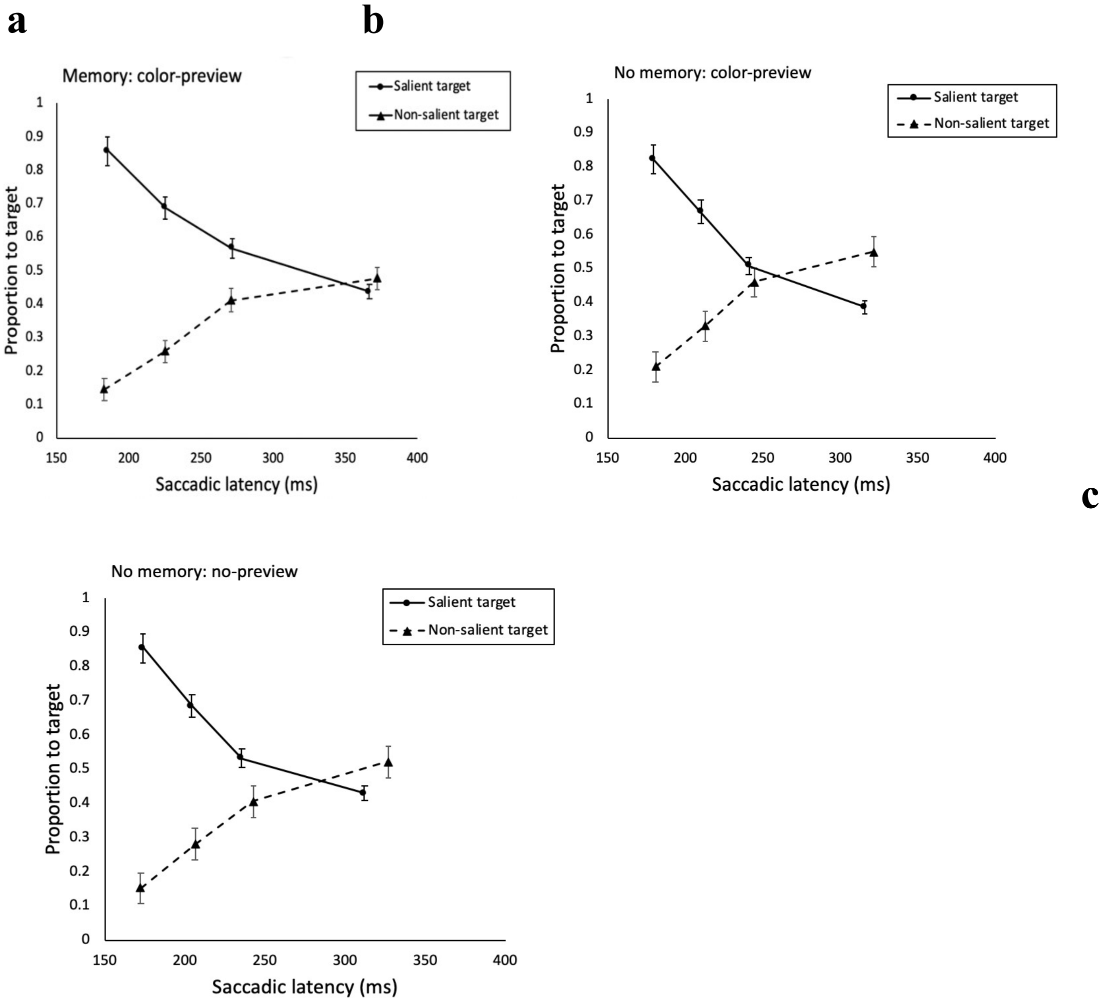

Figure 11. The overall distribution of correct to the salient and non-salient target as a function of saccade latency in the color-memory condition (a), the color-preview nomemory condition (b), in the no-preview no-memory condition (c). Error bars are SEM.

3.3.3 Pupil Response

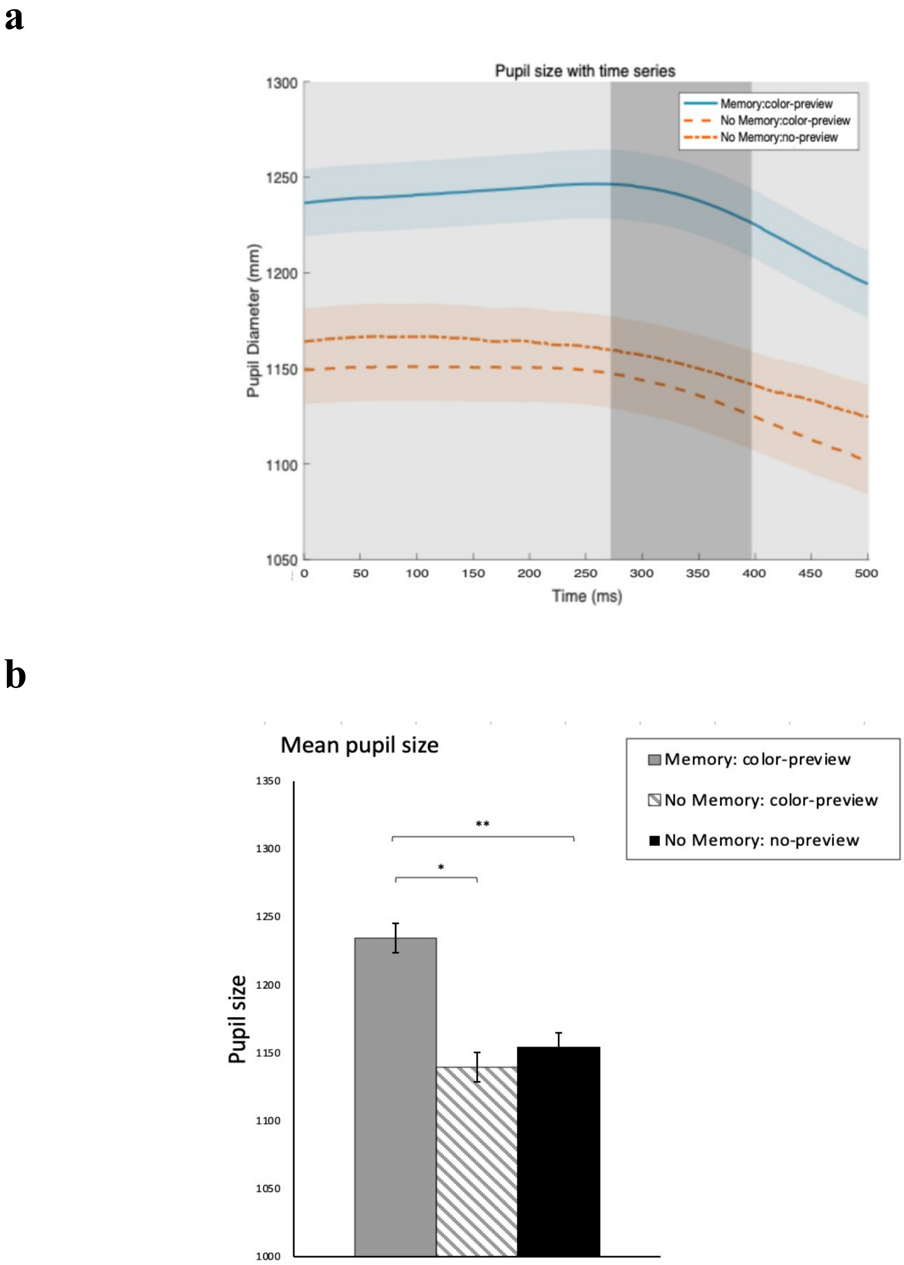

Figure 12. The changes in pupillary diameter during the presentation of each memory array in three conditions (a). Average pupil diameter in different conditions (b). In Figure. 12a, the shaded areas around the pupil reaction indicate the range of ± standard errors (across participants). A dark shaded background indicates $0.01 < p < 0.05$ and the light shaded background represents $p < 0.01$. In figure 12.b, error-bars indicate ± standard errors across participants. * indicates $p < 0.05$. ** indicates $p < 0.01$.

The dynamics of pupil diameters during the presentation of the memory array in Experiment 2 are shown in Figure. 12a. As in Experiment 1, the initial pupil diameter was pre-processed based on the baseline pupil correction procedure. Figure. 12a shows pupil dynamics during the same period of memory stimulus presentation (0-500 ms), illustrating initial pupil dilation after the color-preview or no-preview in all three conditions (the color-memory condition, the color-preview no-memory condition and the no-preview no-memory condition). A series of independent sample t-tests were conducted for pupil size at each millisecond time point for the color-memory and colorpreview no-memory conditions, the color-memory and no-preview no-memory conditions, the color-preview no-memory and no-preview no-memory conditions, respectively. The difference between the color-memory and color-preview no-memory conditions were significant throughout the memory display presentation (significant points in time: 277-398 ms, $p < 0.01$; 0-276 and 390-500 ms, $p < 0.001$). The difference between the color-memory condition and no-preview no-memory conditions was found (0-500 ms, $p < 0.01$).

Figure. 12b shows that the mean pupil size was 1.234 mm, 1.141 mm and 1.157 mm in the color-memory, color-preview no-memory and no-preview no-memory conditions. A repeated-measures ANOVA was performed on the mean pupil diameter with the preview-memory type (color-memory vs. color-preview no-memory vs. nopreview no-memory) as variables. The results indicated that preview-memory had significant effects on the mean pupil size, F (2, 23) = 4.58, $p < 0.05$. The results of posthoc comparisons further showed that pupil size in the color-memory condition (mean 1.234 mm) was larger than the color-preview no memory (mean 1.141 mm), $p < 0.05$, and color-preview no-memory conditions (mean 1.157 mm), $p < 0.01$.

3.3 DISCUSSION

In Experiment 2, the effects of the color-preview were investigated to test how active-memory and no-memory affected oculomotor capture by color-salience. Compared to Experiment 1, the results of Experiment 2 showed that the time-course of saccade selection only rely on the stimulus saliency, suggesting earlier stimulus-driven capture and more goal-directed control later during oculomotor capture. Looking at the overall pattern of the saccade, as the preview-memory types based on color were shared across Experiment 1 and 2, a further mixed-design ANOVA was conducted. We found that there was no reliable three-way interaction among preview-memory (i.e., colormemory vs. color-preview no-memory), target-salience and Experiment (1 vs. 2). This suggested that the difference as a function of target-salience between the color-memory and color-preview no-memory conditions was similar in both experiments. Thus, the further test indicated that memorizing the colors caused more oculomotor capture by color saliency than no-memory, whereas more saccades were directed toward nonsalient items when viewing the color-preview without memory compared to activememory, as evidenced by a two-way interaction between preview-memory (colormemory vs. color-preview no-memory) and target-salience while ignoring the nopreview in Experiment 2. Nevertheless, there was no such difference between colormemory and no-preview no-memory conditions. In other words, color-memory facilitated more saliency-driven saccades than when viewing the no-preview. These findings supported that only when memory-content overlapped with saliency, activememory could enhance color-salience processing. Not only that, in the longest saccade latency, there was an evident inhibition of task-irrelevant color when viewing the colorpreview, which is beneficial for target search performance in the salient-distractor condition relative to the intuitively easier salient-target condition. Meanwhile, no such inhibition was observed in the color-memory and no-preview no-memory conditions even if the saccade latency was the longest.

Furthermore, the increase in oculomotor capture by non-saliency when viewing the color-preview is not simply due to the availability of memory resources. More saccades to non-salient items should be observed in the no-preview no-memory condition than in the active-memory condition, if only more available memory resources could top-down modulate saccades to non-salient targets and deviate from color-salience during later overt selection. Our findings, therefore, suggest that this inhibitory effect on color-saliency is more likely attributable to the role of the colorpreview that shares the same feature as the stimuli. Previous literature has shown that the attentional system uses a number of mechanisms to select items for more detailed cognitive processing when a range of distractors are present in the visual environment. One such mechanism is the ability to prioritize new information, as previously attended items tend to be suppressed (Carmi & Itti, 2006; McCarley et al., 2003; M. Posner & Cohen, 1984). We speculate that the color-preview effect is likely the ability to actively bias away from the old item (i.e., color) and select the new item (i.e., orientation) in a top-down fashion. This saccadic bias away from old features may be supported by studies on the color-based active suppression (Braithwaite et al., 2003; D. G. Watson & Humphreys, 1997). In fact, some researchers have shown that the inhibition of old color features and the prioritization of new features rely on bottom-up changes associated with the appearance of these items (Donk & Theeuwes, 2001, 2003; Pratt et al., 2007). If top-down inhibition of old items is actually a product by stimulus-driven, novel items should always be prioritized, regardless of the load on attention or memory. Our findings argue against this claim; when color-memory resources were taxed, there was no apparent inhibition of color-saliency. Thus, we propose that the color-preview effect cannot be driven by stimulus properties alone but may rely on general ability-limited resources.

As in Experiment 1, the effect of stimulus salience on the time-course of overt oculomotor selection was also demonstrated by the two-way interaction between targetsaliency and bin observed in Experiment 2. When the saccade latency was shorter, more saccades were driven to salient items, even though the salient item were irrelative to the current goal. However, at later times, more saccades were attracted to non-salient targets and greatly improved the correct search performance. This is in line with previous reports that eye movements are automatically directed to salient items at early stages while more target-directed saccades are then performed at later stages (e.g., van Zoest et al., 2008). Salience-driven and goal-directed processes operate at different time points. However, memory-content and memory-type did not modulate such dynamics of saccade selection.

Performance on the probe detection task showed that the color-preview nomemory condition had a much higher working memory accuracy than the colormemory condition. Turning back to the behavioral results shown in Experiment 1, when comparing the color-memory condition to the shape-memory condition, the behavioral responses for memory probe detection had opposite consequences to the overt saccade responses for the visual search task. In Experiment 2, compared to the color-memory condition, better working memory performance was observed in the color-preview nomemory condition. When remembering colors, the average pupil dilation was significantly greater than when viewing the color-preview. The pupil response also indicated that maintaining color information in working memory consumed more cognitive resources. However, the difference in saccade performance was not significant between active-memory and no-memory. While memorizing the colorpreview taxed more resources, it did not affect saccade selection. This finding argues against that working memory taxes executive control in a general way (e.g., Lavie & De Forckert, 2005).

Overall, in this chapter, the results in Experiment 2 also demonstrated the correlations between the memory content based on color information and overt selection. Oculomotor capture by color-salience was enhanced by active-memory compared with no-memory with the color-preview whereas the increase in saccades directed to non-salient items was evident when viewing the color-preview. Moreover, for the longest latency, the difference between the salient-target and salient-distractor conditions as a function of memory-type was large only for the color-preview. While there was an inhibition of color-salience in the color-preview no-memory condition, less inhibition was obtained in the color-memory and no-preview no-memory conditions. Third, the effects of target-salience on overt selection changed significantly as a function of time, earlier stimulus-elicited capture and more goal-directed control later during oculomotor capture. However, working memory did not further modulate such dynamics of overt selection. These findings were replicated in both experiments and provide further evidence for a link between overt oculomotor selection and working memory.

CHAPTER 4 – GENERAL DISCUSSION

The purpose of this study was to determine how working memory content influences dynamic oculomotor capture and how the relationship between search stimuli and memory content moderates this correlation. This chapter contains discussions of the primary findings, as well as relevant literature on the role of memory content in guiding and inhibiting attentional capture by memory-matching items and how overt selection performed as a function of time-course. A discussion of the connections to this study and theoretical implications is also included. The chapter concludes with a discussion of the limitations of the present study, areas for future research, and a summary.

Chapter 4 consists of the discussions of findings from Experiment 1 and 2, as well as possibilities for future studies to help address these research questions:

RQ1: How overt oculomotor selection is affected by memory-content, and whether the overlap between memory-content and stimuli-salience can modulate this relationship.

RQ2: Whether memory content affects dynamics of oculomotor capture, entirely automatic or more strategically and flexibly.

RQ3: As for physical salience, whether active-memory can enhance oculomotor capture by saliency compared with no-memory.

The critical findings from Experiment 1 for how the relationship between memory-content and stimulus-salience modulated oculomotor capture by physical salience, including the following:

(a) Stimulus salience can attract oculomotor capture involuntarily even if that salient singleton was task-irrelevant. Moreover, saliency can affect the time-course of oculomotor selection. Specifically, more saccades were guided toward the salient but task-irrelevant item earlier during overt selection, suggesting a more stimulus-driven capture. Whereas more saccades were directed toward the non-salient target later in time, indicating the more goal-directed control. However, memory-content and memory-type did not modulate such dynamics of overt oculomotor selection.

(b) Active-memory can enhance oculomotor capture by color-salience only when it matches to the memory content (i.e., color-memory). Memorizing shape information without the same features as search stimuli did not show this influence. When memory contents overlapped with stimulus salience, active-memory enhances oculomotor capture by color-salience relative to when memorizing the preview based on shape information (i.e., shape-memory). In addition, the difference as a function of targetsaliency was greatly large only between the color-memory and color-preview nomemory conditions. Compared with no-memory, memorizing the color-preview significantly increased the likelihood of oculomotor capture by color-salience, suggesting more automatic stimulus-driven capture. However, no such difference could be observed between the shape-memory and shape-preview no-memory conditions, as well as color-memory and no-preview no-memory conditions.

(c) For the longest saccade latency (i.e., the fourth bin), the post-hoc test for each condition revealed that the difference in proportions of saccade-to-target between salient-target and non-salient target as a function of memory-type was dramatically larger for the color condition, compared to both the shape condition in Experiment 1 and the no-preview condition in Experiment 2. Specifically, viewing the color-preview showed the evident inhibition of irrelevant color. However, color-memory showed less inhibition of color-saliency, even when saccade latencies were the longest. This finding suggests that when memory-content matched to stimuli saliency, passively viewing the color-preview signalling the search salience can improve the search performance in the intuitively more complex salient-distractor condition by deviating from saliency in a top-down manner.

4.1 FINDINGS & IMPLICATIONS

Experiment 1 first showed the the time-course of overt selection was only affected by stimulus saliency as bin was only seen to interact with target-saliency. When the time-course factor was not considered, more saccades were directed toward salient items even though the target was salient, suggesting physical saliency can bias overt selection in an involuntary process. After the time-course factor was taken into consideration, saliency cannot always attract eye movements. Specifically, more saccades were guided to the salient item as early stages of visual search, whereas more to the non-salient items and benefited the search performance in the salient-distractor condition later in time. This dynamic of overt oculomotor selection revealed two independent processes – earlier involuntary stimulus-driven and later voluntary goaldirected – would occur in different time windows (e.g., van Zoest & Donk, 2008).

The important finding is that memory-content can play an important role in orientation of oculomotor selection. The influence of memory-content on oculomotor capture by color-saliency depends on the relationship between memory-content and stimulus-saliency. Active-memory can significantly enhance the color-salience processing only when saliency matches to memory-content. As observed by the reliable three-way interaction among memory-content, memory-preview and target-saliency, color-memory directed more saccades toward color-saliency relative to shape-memory. Looking specifically at the color-condition, there was the two-way interaction between memory-content and target-saliency only for the color-preview but not the shapepreview. While memorizing the colors enhanced saliency-driven processing compared with no-memory, viewing the color-preview reduced the likelihood of oculomotor capture by saliency and directed more saccades toward non-salient items. However, such difference as a function of target-saliency was not observed for the shape condition. In addition, the post-hoc follow-up test indicated that memorizing the colors caused more saccades to the salient item than the non-salient item even if the distractor was salient (e.g., Soto et al., 2008), suggesting a stimulus-driven process. However, the difference between the salient target and the non-salient target conditions was not observed in the color-preview no-memory condition. Thus, the greater interference from physical saliency was observed only when stimulus saliency was matched to memory content, which is a novel finding of this study.

This finding is consistent with previous work (e.g., Awh et al., 1998; Downing, 2000; Pashler & Shiu, 1999). They claimed that working memory content allows memory-matching stimuli to gain more advantage in automatically capturing oculomotor selection, even when the stimulus is task-irrelevant. In addition, compared with color-memory, shape-memory directed more saccades to the non-salient target and fewer to the salient target. This also supports the idea that oculomotor capture of memory-matching stimuli is less likely when the modalities of memory information and search stimuli are different (Kim et al., 2005; Downing & Dodds, 2004).

The priming effect of the color-preview was also prominent, that is, passively viewing the color-preview significantly reduced the interference from color-saliency. Compared to viewing the color-preview, viewing the shape-preview increased oculomotor capture by salient items and decreased by non-salient items, as observed by the two-way interaction between memory-content and target-saliency at the level of nomemory in Experiment 1. Furthermore, post-hoc tests of the fourth bin at later stages of visual search also demonstrated that viewing the color-preview guided more saccades toward non-salient items than to salient items, namely, an evident suppression of irrelevant colors (see Figure 6c) in Experiment 1. In contrast, viewing the shapepreviews did not have this suppression. This is consistent with the preview effect proposed by some researchers, which is the active top-down suppression of previously presented old items (i.e., colors) in favor of prioritization of new items that appear in the subsequent search display. One demonstration of the ability to prioritize new information comes from the preview search literature (D. G. Watson & Humphreys, 1997). Watson and Humphreys found that when a subset of distractors in a conjunction search task is previewed before the remaining distractors and targets are presented, the search slope is significantly reduced relative to the search slope when all distractors and targets are presented at the same time. They initially proposed top-down attentional suppression of previewed items, which enabled prioritization of new items through a process described as visual tagging. Other studies also provided evidence that nonspatial feature (e.g., color) may improve the entry of information into the brain (Brawn & Snowden, 1999; Laarni, 1999; Lambert & Corban, 1992; Lappin & Uttal, 1976; Vierck & Miller, 2005). For example, von Wright (1970) showed efficient selection in a partial report task on the basis of simple attributes such as color, luminance and shape (Bundesen et al., 1984).

Some researchers, however, proposed that perceptual sensitivity is influenced by a top-down set of spatial information but not by a top-down set of non-spatial information (Cave & Pashler, 1995; M.-S. Kim & Cave, 2001; M. I. Posner, 1980; Jan Theeuwes, 1989; Jan Theeuwes & Van der Burg, 2008). Perceptual sensitivity can be enhanced by non-spatial features, but only through processes associated with bottomup priming. Van der Heijden found that non-spatial information points to locations in the display (similar to bar markers indicating location) and ultimately location is used as a means of selecting relevant items (Tsal & Lavie, 1988). For example, in the experiments of Shih and Sperling (1996), a rapid visual sequence presentation paradigm consisting of a series of stimuli superimposed on each other was used. The results showed that participants were able to better detect the target-digit when it was their desired color (or size), but only when it was in a frame with distractors of various colors (Shih & Sperling, 1996). Clearly, in this condition, the expected non-spatial features provide spatial information about the target. In the condition where elements in a single frame had the same color, the expected non-spatial features provided temporal information, but no spatial information, which participants could not use to improve performance. Thus, they concluded that non-spatial information did not directly influence visual selection but only by guiding spatial attention to relevant positions.

Our findings provide some insight into the underlying mechanisms of this preview effect. If the preview effect is largely independent of the limits of cognitive processing (i.e., driven by novel stimulus properties), then regardless of the level of memory or attentional load, there should be little or no limit to the inhibition of old items. Novelty items that have not previously appeared are always given priority when the benefit of previewing is a product of stimulus drive (Donk & Theeuwes, 2001, 2003; Pratt et al., 2007). If the ability to prioritize novel information is top-down inhibited, it should be limited by cognitive resources. In this study, we found this preview effect to be limited. This was manifested as a significant inhibition of color-saliency when viewing only the color-previews without memory; this inhibition was not present when actively remembering colors, suggesting that the ability to suppress preview items may depend on some capacity-limited resource. Active-memory competes for the resources that are required to actively inhibit old items, resulting in inhibition that cannot be observed in the color-memory condition. In addition, in the salient-target condition where the target had the same feature with other stimuli (i.e., white) whereas the distractor had a different color from others, there were no more saccades directed toward the distractor when viewing the color-preview. This suggests that the color information is not entirely attributable to point out the relevant position and purely directs attention in a bottomup way. Thus, we propose that color-preview effects cannot be driven by stimulus properties alone but may also depend on general capacity-limited resources (Emrich et al., 2008).

Furthermore, in Experiment 1, saccade performance in the shape-memory condition was generally better than that in the color-memory condition, but its memory performance was lower than color-memory. We speculated that the reason for this lies in the fact that the task of remembering shapes is more difficult compared to remembering colors. Pupil size was also significantly larger in the shape memory condition than in the color memory condition, implying that remembering shapes requires more cognitive resources. Moreover, even though the shape-memory task was more complex and required more cognitive resources than the color-memory task, it did not affect visual selection. This also indirectly demonstrates that the effect of working memory on overt oculomotor selection depends on the relationship between memory-content and search stimuli.

Experiment 2 expanded the understanding of the association between memory content and oculomotor capture by further investigating the effect of the color-preview that overlap with saliency and the no-preview on oculomotor capture by saliency. First, the same effect of stimulus saliency was found as in Experiment 1. Stimulus saliency significantly affected saccade selection over the time-course, involuntarily attracting more saccades in the early stages even when saliency was task-irrelevant. As with the bottom-up saccade selection model, initial selection is dominated by saliency (Engel, 1977; Jan Theeuwes et al., 1999; Jan Theeuwes & Godijn, 2001, 2002; van Zoest & Donk, 2004, 2005). However, in the late stages, more eye movements were directed to the target even though it was non-salient, improving search performance especially for the salient-distractor condition (Cheal & Chastain, 2002; Ludwig & Gilchrist, 2002; Müller & Rabbitt, 1989; Van Zoest & Donk, 2008). These results support the relative contribution of stimulus-induced and target-driven saccades to the time course during visual search. The saccadic selection is controlled by stimulus saliency in a bottomup way predominantly. More saccades were first evoked to the salient stimulus in a bottom-up way. But later in time, more target-driven eye movements occurred in a topdown manner and selected non-salient stimuli (Nakayama & Mackeben, 1989;

Trappenberg et al., 2001). However, working memory did not modulate such dynamics of selection.

Most importantly, the results of a mixed-design ANOVA indicated that the three-way interaction was not significant, suggesting that the relationship between preview-memory and target-salience in Experiment 2 was the same as in Experiment 1. Further, there was a reliable interaction between memory-type and memory-content while ignoring the no-preview condition. This demonstrated that the impact of irrelevant colors on oculomotor capture was significantly reduced in the color-preview no-memory condition compared to the color-memory condition. In addition, there were no more saliency-driven saccades for the color-memory condition than for the nopreview control condition. These findings replicated the important finding of Experiment 1 that active-memory had a modulatory effect on oculomotor capture by physical salience only when it matched to memory-content. Compared to the study by Lavie and colleagues (2005), a working memory task required memorizing an array of digits and searching for shape targets. They found that memory load can increase the capture of salient distractors because color items are more salient and can compete strongly with target shapes. Conversely, the availability of working memory resources can favour non-target rejection. Thus, the general role of working memory in the goaldirected control of visual attentional selection minimizes the interference of any goalirrelevant distractors. This is inconsistent with our findings for shape-memory. We failed to observe a difference between executive-control of the shape-memory and viewing the shape-preview on oculomotor capture by color-saliency. Memorizing the shape-preview did not significantly enhance oculomotor capture by saliency compared with viewing the shape-preview. Working memory modulated oculomotor capture by irrelevant color-saliency only when it overlapped with memory-content. This suggests that working memory does not affect overt selection in a general way, but rather based on content-specific.

As in Experiment 1, there was also the prominent color-preview effect in Experiment 2. Specifically, in the overall eye-movement performance, viewing the color-preview guided more saccades toward non-salient items than the no-preview and color-memory conditions, benefiting the search performance in the salient-distractor condition. In addition, while viewing the color-preview showed the suppression of irrelevant colors in the longest saccade latency, neither of the other two conditions had such suppression. These findings also support the idea that the color-preview effect is a top-down process of actively inhibiting old items (i.e., color) and preferring new items (i.e., orientation). Thus, the inhibition of irrelevant color may rely on general capacitylimited resources shared with memory processes. This pattern of search performance can be explained in an alternative way, in which the interaction between selective attention and working memory can be strategically implemented to optimize performance. As recently suggested by Olivers et al. (2011), memory objects can be maintained in different activation states, determining the extent to which they influence attention allocation. Passively viewing the color-preview may not achieve the significant effects of explicit color memory but will intentionally activate color representations and become more sensitive to color information. Thus, the inhibition of color-saliency can be achieved.

4.2 FUTURE DIRECTIONS

In the present work, we investigated oculomotor selection by considering the initial landing location, saccade latency, and pupil dilation. Since the memory-content effect of color-preview was tested independently in Experiment 2, we also consider the follow up experiment on a single shape dimension. The memory-preview will be based on shape information only, and saliency will be defined as a specific shape. For features that overlap with working memory representations, findings of increased oculomotor capture by shape-saliency in the shape-memory condition and increased inhibitory control in the shape-preview no-memory condition would be expected. However, there are some troubles in implementing this idea, especially how to specify a salient shape in visual search. In the current search task, the difference between targets, distractors and non-targets was determined by the orientations of lines. Thus, our challenge is to appropriately use the shape as saliency and assign it to the target or distractor.

In addition, we are also interested in whether memory-load can modulate the relationship between memory-content and oculomotor capture. Therefore, to properly define the memory-load condition, in the future study we will manipulate memory-load levels above zero, such as remembering four items for low-load and eight items for high-load. We can also evaluate this in future studies with other parameters to help extend the current findings, such as micro-saccadic movements (Engbert & Kliegl, 2003; Hafed & Clark, 2002).

4.3 CONCLUDING REMARKS

In summary, our findings provide direct evidence that oculomotor captured by irrelative salience was enhanced by active-memory only when memory-content overlapped with the stimulus-saliency. This suggests that working memory affects overt selection in a content-specific way rather than a general manner (e.g., Lavie & De Forckert, 2005). Second, the time-course of saccade selection can be influenced by only stimulus saliency, showing the early automatic stimulus-elicited and later voluntary goal-directed control processes. Further, the inhibition of irrelevant saliency was observed only when viewing the color-preview, suggesting a top-down active control.

References

Anderson, S. F., Kelley, K., & Maxwell, S. E. (2017). Sample-size planning for more accurate statistical power: A method adjusting sample effect sizes for publication bias and uncertainty. *Psychological Science*, *28*(11), 1547–1562.

Arita, J. T., Carlisle, N. B., & Woodman, G. F. (2012). Templates for rejection: Configuring attention to ignore task-irrelevant features. *Journal of Experimental Psychology. Human Perception and Performance*, *38*(3), 580–584. https://doi.org/10.1037/a0027885

Awh, E., Belopolsky, A. V., & Theeuwes, J. (2012). Top-down versus bottom-up attentional control: A failed theoretical dichotomy. *Trends in Cognitive Sciences*, *16*(8), 437–443.

Awh, E., Jonides, J., & Reuter-Lorenz, P. A. (1998). Rehearsal in spatial working memory. *Journal of Experimental Psychology: Human Perception and Performance*, *24*(3), 780.

Baddeley, A. (1993). Working memory and conscious awareness. *Theories of Memory*, 11–28.

Beck, V. M., Luck, S. J., & Hollingworth, A. (2018). Whatever you do, don't look at the . . .: Evaluating guidance by an exclusionary attentional template. *Journal of Experimental Psychology: Human Perception and Performance*, *44*(4), 645–662. https://doi.org/10.1037/xhp0000485

Belopolsky, A. V., & Theeuwes, J. (2009). When Are Attention and Saccade Preparation Dissociated? *Psychological Science*, *20*(11), 1340–1347. https://doi.org/10.1111/j.1467-9280.2009.02445.x

Berggren, N., & Eimer, M. (2018). Electrophysiological correlates of active suppression and attentional selection in preview visual search. *Neuropsychologia*, *120*, 75–85. https://doi.org/10.1016/j.neuropsychologia.2018.10.016

Braithwaite, J. J., Humphreys, G. W., & Hodsoll, J. (2003). Color Grouping in Space and Time: Evidence From Negative Color-Based Carryover Effects in Preview

Search. *Journal of Experimental Psychology: Human Perception and Performance*, *29*(4), 758–778. https://doi.org/10.1037/0096-1523.29.4.758

Brawn, P., & Snowden, R. J. (1999). Can one pay attention to a particular color? *Perception & Psychophysics*, *61*(5), 860–873.

Bundesen, C., Pedersen, L. F., & Larsen, A. (1984). Measuring efficiency of selection from briefly exposed visual displays: A model for partial report. *Journal of Experimental Psychology: Human Perception and Performance*, *10*(3), 329.

Burnham, B. R., Sabia, M., & Langan, C. (2014). Components of working memory and visual selective attention. *Journal of Experimental Psychology: Human Perception and Performance*, *40*(1), 391–403. https://doi.org/10.1037/a0033753

Buswell, G. T. (1935). *How people look at pictures: A study of the psychology and perception in art* (p. 198). Univ. Chicago Press.

Carlisle, N. B., & Kristjánsson, Á. (2018). How visual working memory contents influence priming of visual attention. *Psychological Research*, *82*(5), 833–839. https://doi.org/10.1007/s00426-017-0866-6

Carmi, R., & Itti, L. (2006). Visual causes versus correlates of attentional selection in dynamic scenes. *Vision Research*, *46*(26), 4333–4345. https://doi.org/10.1016/j.visres.2006.08.019

Castelhano, M. S., Mack, M. L., & Henderson, J. M. (2009). Viewing task influences eye movement control during active scene perception. *Journal of Vision*, *9*(3), 1–15.

Cave, K. R., & Pashler, H. (1995). Visual selection mediated by location: Selecting successive visual objects. *Perception & Psychophysics*, *57*(4), 421–432. https://doi.org/10.3758/BF03213068

Cheal, M., & Chastain, G. (2002). Timing of facilitatory and inhibitory effects of visual attention. *Visual Cognition*, *9*(8), 969–1002.

Chun, M. M. (2011). Visual working memory as visual attention sustained internally over time. *Neuropsychologia*, *49*(6), 1407–1409.

Conci, M., Müller, H. J., & Mühlenen, A. von. (2013). Object-based implicit learning in visual search: Perceptual segmentation constrains contextual cueing. *Journal of Vision*, *13*(3), 15–15. https://doi.org/10.1167/13.3.15

Corbetta, M., & Shulman, G. L. (2002). Control of goal-directed and stimulus-driven attention in the brain. *Nature Reviews Neuroscience*, *3*(3), 201–215.

Corneil, B. D., & Munoz, D. P. (2014). Overt Responses during Covert Orienting. *Neuron*, *82*(6), 1230–1243. https://doi.org/10.1016/j.neuron.2014.05.040

Cowan, N. (1999). An embedded-processes model of working memory. *Models of Working Memory: Mechanisms of Active Maintenance and Executive Control*, *20*, 506.

Cowan, N., Li, Y., Glass, B. A., & Scott Saults, J. (2018). Development of the ability to combine visual and acoustic information in working memory. *Developmental Science*, *21*(5), e12635.

Cronin, D. A., & Irwin, D. E. (2018). Visual working memory supports perceptual stability across saccadic eye movements. *Journal of Experimental Psychology: Human Perception and Performance*, *44*(11), 1739–1759. https://doi.org/10.1037/xhp0000567

de Fockert, J. W. (2013). Beyond perceptual load and dilution: A review of the role of working memory in selective attention. *Frontiers in Psychology*, *4*. https://doi.org/10.3389/fpsyg.2013.00287

de Fockert, J. W., Rees, G., Frith, C. D., & Lavie, N. (2001). The role of working memory in visual selective attention. *Science*, *291*(5509), 1803–1806.

de Fockert, J. W., & Theeuwes, J. (2012). Role of frontal cortex in attentional capture by singleton distractors. *Brain and Cognition*, *80*(3), 367–373.

De Houwer, J., Hughes, S., & Brass, M. (2017). Toward a unified framework for research on instructions and other messages: An introduction to the special issue on the power of instructions. *Neuroscience & Biobehavioral Reviews*, *81*, 1–3. https://doi.org/10.1016/j.neubiorev.2017.04.020

DeAngelus, M., & Pelz, J. B. (2009). Top-down control of eye movements: Yarbus revisited. *Visual Cognition*, *17*(6–7), 790–811. https://doi.org/10.1080/13506280902793843

Desimone, R., & Duncan, J. (1995). Neural mechanisms of selective visual attention. *Annual Review of Neuroscience*, *18*(1), 193–222.

Deubel, H., & Schneider, W. X. (1996). Saccade target selection and object recognition: Evidence for a common attentional mechanism. *Vision Research*, *36*(12), 1827–1837. https://doi.org/10.1016/0042-6989(95)00294-4

Donk, M., & Theeuwes, J. (2001). Visual marking beside the mark: Prioritizing selection by abrupt onsets. *Perception & Psychophysics*, *63*(5), 891–900. https://doi.org/10.3758/BF03194445

Donk, M., & Theeuwes, J. (2003). Prioritizing selection of new elements: Bottom-up versus top-down control. *Perception & Psychophysics*, *65*(8), 1231–1242. https://doi.org/10.3758/BF03194848

Downing, P., & Dodds, C. (2004). Competition in visual working memory for control of search. *Visual Cognition*, *11*(6), 689–703. https://doi.org/10.1080/13506280344000446

Downing, P. E. (2000). Interactions between visual working memory and selective attention. *Psychological Science*, *11*(6), 467–473.

Emrich, S. M., Ruppel, J. D. N., Al-Aidroos, N., Pratt, J., & Ferber, S. (2008). Out with the old: Inhibition of old items in a preview search is limited. *Perception & Psychophysics*, *70*(8), 1552–1557. https://doi.org/10.3758/PP.70.8.1552

Engbert, R., & Kliegl, R. (2003). Microsaccades uncover the orientation of covert attention. *Vision Research*, *43*(9), 1035–1045.

Engel, F. L. (1977). Visual conspicuity, visual search and fixation tendencies of the eye. *Vision Research*, *17*(1), 95–108.

Folk, C. L., Remington, R. W., & Johnston, J. C. (1992). Involuntary covert orienting is contingent on attentional control settings. *Journal of Experimental Psychology: Human Perception and Performance*, *18*(4), 1030–1044. https://doi.org/10.1037/0096-1523.18.4.1030

Forester, G., Kroneisen, M., Erdfelder, E., & Kamp, S.-M. (2019). On the role of retrieval processes in the survival processing effect: Evidence from ROC and ERP analyses. *Neurobiology of Learning and Memory*, *166*, 107083. https://doi.org/10.1016/j.nlm.2019.107083

Frischen, A., Bayliss, A. P., & Tipper, S. P. (2007). Gaze cueing of attention: Visual attention, social cognition, and individual differences. *Psychological Bulletin*, *133*(4), 694.

Gaspelin, N., & Luck, S. J. (2018). The Role of Inhibition in Avoiding Distraction by Salient Stimuli. *Trends in Cognitive Sciences*, *22*(1), 79–92. https://doi.org/10.1016/j.tics.2017.11.001

Gazzaley, A., & Nobre, A. C. (2012). Top-down modulation: Bridging selective attention and working memory. *Trends in Cognitive Sciences*, *16*(2), 129–135.

Godijn, R., & Theeuwes, J. (2004). The Relationship Between Inhibition of Return and Saccade Trajectory Deviations. *Journal of Experimental Psychology: Human Perception and Performance*, *30*(3), 538–554. https://doi.org/10.1037/0096-1523.30.3.538

Goujon, A., Didierjean, A., & Thorpe, S. (2015). Investigating implicit statistical learning mechanisms through contextual cueing. *Trends in Cognitive Sciences*, *19*(9), 524–533. https://doi.org/10.1016/j.tics.2015.07.009

Greene, C. M., Kennedy, K., & Soto, D. (2015). Dynamic states in working memory modulate guidance of visual attention: Evidence from an n-back paradigm. *Visual Cognition*, *23*(5), 546–560.

Hafed, Z. M., & Clark, J. J. (2002). Microsaccades as an overt measure of covert attention shifts. *Vision Research*, *42*(22), 2533–2545.

Han, suk won, & Kim, M.-S. (2009). Do the Contents of Working Memory Capture Attention? Yes, But Cognitive Control Matters. *Journal of Experimental Psychology. Human Perception and Performance*, *35*, 1292–1302. https://doi.org/10.1037/a0016452

Hasher, L., Zacks, R. T., & Rahhal, T. A. (1999). Timing, instructions, and inhibitory control: Some missing factors in the age and memory debate. *Gerontology*, *45*(6), 355–357.

Heaver, B., & Hutton, S. B. (2011). Keeping an eye on the truth? Pupil size changes associated with recognition memory. *Memory*, *19*(4), 398–405. https://doi.org/10.1080/09658211.2011.575788

Heimler, B., Pavani, F., Donk, M., & van Zoest, W. (2014). Stimulus- and goal-driven control of eye movements: Action videogame players are faster but not better. *Attention, Perception, & Psychophysics*, *76*(8), 2398–2412. https://doi.org/10.3758/s13414-014-0736-x

Heimler, B., van Zoest, W., Baruffaldi, F., Rinaldi, P., Caselli, M. C., & Pavani, F. (2015). Attentional orienting to social and nonsocial cues in early deaf adults. *Journal of Experimental Psychology: Human Perception and Performance*, *41*(6), 1758–1771. https://doi.org/10.1037/xhp0000099

Hess, E. H., & Polt, J. M. (1964). Pupil Size in Relation to Mental Activity during Simple Problem-Solving. *Science*, *143*(3611), 1190–1192. https://doi.org/10.1126/science.143.3611.1190

Hester, R., & Garavan, H. (2005). Working memory and executive function: The influence of content and load on the control of attention. *Memory & Cognition*, *33*(2), 221–233. https://doi.org/10.3758/BF03195311

Hickey, C., van Zoest, W., & Theeuwes, J. (2010). The time course of exogenous and endogenous control of covert attention. *Experimental Brain Research*, *201*(4), 789–796.

Hoffman, J. E., & Subramaniam, B. (1995). The role of visual attention in saccadic eye movements. *Perception & Psychophysics*, *57*(6), 787–795. https://doi.org/10.3758/BF03206794

Hollingworth, A. (2012). Task specificity and the influence of memory on visual search: Comment on Võ and Wolfe (2012). *Journal of Experimental Psychology: Human Perception and Performance*, *38*(6), 1596–1603.

https://doi.org/10.1037/a0030237

Hollingworth, A., & Luck, S. J. (2009). The role of visual working memory (VWM) in the control of gaze during visual search. *Attention, Perception, & Psychophysics*, *71*(4), 936–949.

Hollingworth, A., Matsukura, M., & Luck, S. J. (2013). Visual working memory modulates rapid eye movements to simple onset targets. *Psychological Science*, *24*(5), 790–796.

Hopf, J.-M., & Mangun, G. R. (2000). Shifting visual attention in space: An electrophysiological analysis using high spatial resolution mapping. *Clinical Neurophysiology*, *111*(7), 1241–1257.

Hu, Y., Xu, Z., & Hitch, G. J. (2011). Strategic and automatic effects of visual working memory on attention in visual search. *Visual Cognition*, *19*(6), 799–816. https://doi.org/10.1080/13506285.2011.590461

Hunt, A. R., Mühlenen, A. von, & Kingstone, A. (2007). The time course of attentional and oculomotor capture reveals a common cause. *Journal of Experimental Psychology: Human Perception and Performance*, *33*(2). https://doi.org/10.1037/0096-1523.33.2.271

Johnson, J. S., Hollingworth, A., & Luck, S. J. (2008). The role of attention in the maintenance of feature bindings in visual short-term memory. *Journal of Experimental Psychology: Human Perception and Performance*, *34*(1), 41–55. https://doi.org/10.1037/0096-1523.34.1.41

Kahneman, D., & Beatty, J. (1966). Pupil Diameter and Load on Memory. *Science*, *154*(3756), 1583–1585. https://doi.org/10.1126/science.154.3756.1583

Kane, M. J., Bleckley, M. K., Conway, A. R., & Engle, R. W. (2001). A controlledattention view of working-memory capacity. *Journal of Experimental Psychology: General*, *130*(2), 169.

Kelley, T. A., & Lavie, N. (2011). Working memory load modulates distractor competition in primary visual cortex. *Cerebral Cortex*, *21*(3), 659–665.

Kim, M.-S., & Cave, K. R. (2001). Perceptual grouping via spatial selection in a focused-attention task. *Vision Research*, *41*(5), 611–624.

https://doi.org/10.1016/S0042-6989(00)00285-6

Kim, S.-Y., Kim, M.-S., & Chun, M. M. (2005). Concurrent working memory load can reduce distraction. *Proceedings of the National Academy of Sciences*, *102*(45), 16524–16529. https://doi.org/10.1073/pnas.0505454102

Kiyonaga, A., & Egner, T. (2014). The working memory Stroop effect: When internal representations clash with external stimuli. *Psychological Science*, *25*(8), 1619–1629.

Kiyonaga, A., Egner, T., & Soto, D. (2012). Cognitive control over working memory biases of selection. *Psychonomic Bulletin & Review*, *19*(4), 639–646. https://doi.org/10.3758/s13423-012-0253-7

Klingner, J., Tversky, B., & Hanrahan, P. (2011). Effects of visual and verbal presentation on cognitive load in vigilance, memory, and arithmetic tasks. *Psychophysiology*, *48*(3), 323–332.

Koch, R. A., & Caldwell, H. M. (2006). *Simultaneous visual and telephonic access to interactive information delivery*. Google Patents.

Koelewijn, T., Bronkhorst, A. W., & Theeuwes, J. (2008). *Auditory capture during focused visual attention*.

Kowler, E., Anderson, E., Dosher, B., & Blaser, E. (1995). The role of attention in the programming of saccades. *Vision Research*, *35*(13), 1897–1916. https://doi.org/10.1016/0042-6989(94)00279-U

Kret, M. E., & Sjak-Shie, E. E. (2019). Preprocessing pupil size data: Guidelines and code. *Behavior Research Methods*, *51*(3), 1336–1342. https://doi.org/10.3758/s13428-018-1075-y

Laarni, J. (1999). Allocating attention in the visual field: The effects of cue type and target–distractor confusability. *Acta Psychologica*, *103*(3), 281–294. https://doi.org/10.1016/S0001-6918(99)00045-1

Lambert, A. J., & Corban, R. (1992). Spatial attention and expectancy for colour, category and location: Further evidence against the spotlight model. *Acta Psychologica*, *81*(1), 39–51. https://doi.org/10.1016/0001-6918(92)90010-B

Lamy, D., Tsal, Y., & Egeth, H. E. (2003). Does a salient distractor capture attention early in processing? *Psychonomic Bulletin & Review*, *10*(3), 621–629. https://doi.org/10.3758/BF03196524

Lappin, J. S., & Uttal, W. R. (1976). Does prior knowledge facilitate the detection of visual targets in random noise? *Perception & Psychophysics*, *20*(5), 367–374. https://doi.org/10.3758/BF03199417

Lavie, N. (2005). Distracted and confused?: Selective attention under load. *Trends in Cognitive Sciences*, *9*(2), 75–82.

Lavie, N., & De Fockert, J. (2005). The role of working memory in attentional capture. *Psychonomic Bulletin & Review*, *12*(4), 669–674. https://doi.org/10.3758/bf03196756

Lavie, N., & de Fockert, J. (2006). Frontal control of attentional capture in visual search. *Visual Cognition*, *14*(4–8), 863–876. https://doi.org/10.1080/13506280500195953

Lavie, N., Hirst, A., De Fockert, J. W., & Viding, E. (2004). Load theory of selective attention and cognitive control. *Journal of Experimental Psychology: General*, *133*(3), 339.

Lewis-Peacock, J. A., Kessler, Y., & Oberauer, K. (2018). The removal of information from working memory. *Annals of the New York Academy of Sciences*, *1424*(1), 33–44.

Lu, J., Tian, L., Zhang, J., Wang, J., Ye, C., & Liu, Q. (2017). Strategic inhibition of distractors with visual working memory contents after involuntary attention capture. *Scientific Reports*, *7*(1), 1–9. https://doi.org/10.1038/s41598-01716305-5

Luck, S. J., & Vogel, E. K. (1997). The capacity of visual working memory for features and conjunctions. *Nature*, *390*(6657), 279–281. https://doi.org/10.1038/36846

Ludwig, C. J., & Gilchrist, I. D. (2002). Stimulus-driven and goal-driven control over visual selection. *Journal of Experimental Psychology: Human Perception and Performance*, *28*(4), 902.

Mannan, S. K., Kennard, C., Potter, D., Pan, Y., & Soto, D. (2010). Early oculomotor capture by new onsets driven by the contents of working memory. *Vision Research*, *50*(16), 1590–1597.

Marshall, L., & Bays, P. M. (2013). Obligatory encoding of task-irrelevant features depletes working memory resources. *Journal of Vision*, *13*(2), 21–21.

Mathôt, S., Schreij, D., & Theeuwes, J. (2012). OpenSesame: An open-source, graphical experiment builder for the social sciences. *Behavior Research Methods*, *44*(2), 314–324.

McCabe, D. P., Roediger, H. L., McDaniel, M. A., Balota, D. A., & Hambrick, D. Z. (2010). The relationship between working memory capacity and executive functioning: Evidence for a common executive attention construct. *Neuropsychology*, *24*(2), 222–243. https://doi.org/10.1037/a0017619

McCarley, J. S., Wang, R. F., Kramer, A. F., Irwin, D. E., & Peterson, M. S. (2003). How Much Memory Does Oculomotor Search Have? *Psychological Science*, *14*(5), 422–426. https://doi.org/10.1111/1467-9280.01457

Meghanathan, R. N., van Leeuwen, C., & Nikolaev, A. R. (2015). Fixation duration surpasses pupil size as a measure of memory load in free viewing. *Frontiers in Human Neuroscience*, *8*. https://doi.org/10.3389/fnhum.2014.01063

Moher, J., & Egeth, H. E. (2012). The ignoring paradox: Cueing distractor features leads first to selection, then to inhibition of to-be-ignored items. *Attention, Perception, & Psychophysics*, *74*(8), 1590–1605. https://doi.org/10.3758/s13414-012-0358-0

Mulckhuyse, M., van Zoest, W., & Theeuwes, J. (2008). Capture of the eyes by relevant and irrelevant onsets. *Experimental Brain Research*, *186*(2), 225–235.

Müller, H. J., & Rabbitt, P. M. (1989). Reflexive and voluntary orienting of visual attention: Time course of activation and resistance to interruption. *Journal of Experimental Psychology: Human Perception and Performance*, *15*(2), 315.

Naber, M., Frässle, S., Rutishauser, U., & Einhäuser, W. (2013). Pupil size signals novelty and predicts later retrieval success for declarative memories of natural scenes. *Journal of Vision*, *13*(2), 11–11. https://doi.org/10.1167/13.2.11

Nakayama, K., & Mackeben, M. (1989). Sustained and transient components of focal visual attention. *Vision Research*, *29*(11), 1631–1647.

Nieuwenstein, M., & Potter, M. (2007). Continuous target input overrides the attentional blink in rapid serial visual presentation. *Journal of Vision*, *7*(9), 813–813. https://doi.org/10.1167/7.9.813

Oberauer, K. (2019). Working memory and attention–A conceptual analysis and review. *Journal of Cognition*, *2*(1).

Oberauer, K., Awh, E., & Sutterer, D. W. (2017). The role of long-term memory in a test of visual working memory: Proactive facilitation but no proactive interference. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *43*(1), 1.

O'Craven, K. M., Downing, P. E., & Kanwisher, N. (1999). FMRI evidence for objects as the units of attentional selection. *Nature*, *401*(6753), 584–587. https://doi.org/10.1038/44134

Olivers, C. N. (2008). Interactions between visual working memory and visual attention. *Frontiers in Bioscience*, *13*(3), 1182–1191.

Olivers, C. N. (2009). What drives memory-driven attentional capture? The effects of memory type, display type, and search type. *Journal of Experimental Psychology: Human Perception and Performance*, *35*(5), 1275.

Olivers, C. N., Meijer, F., & Theeuwes, J. (2006). Feature-based memory-driven attentional capture: Visual working memory content affects visual attention. *Journal of Experimental Psychology: Human Perception and Performance*, *32*(5), 1243.

Olivers, C. N., Peters, J., Houtkamp, R., & Roelfsema, P. R. (2011). Different states in visual working memory: When it guides attention and when it does not. *Trends in Cognitive Sciences*, *15*(7), 327–334.

Otero, S. C., Weekes, B. S., & Hutton, S. B. (2011). Pupil size changes during recognition memory. *Psychophysiology*, *48*(10), 1346–1353. https://doi.org/10.1111/j.1469-8986.2011.01217.x

Palangi, H., Deng, L., Shen, Y., Gao, J., He, X., Chen, J., Song, X., & Ward, R. (2016). Deep sentence embedding using long short-term memory networks: Analysis and application to information retrieval. *IEEE/ACM Transactions on Audio, Speech, and Language Processing*, *24*(4), 694–707.

Park, S., Kim, M.-S., & Chun, M. M. (2007). Concurrent working memory load can facilitate selective attention: Evidence for specialized load. *Journal of Experimental Psychology: Human Perception and Performance*, *33*(5), 1062.

Pashler, H., & Shiu, L. (1999). Do images involuntarily trigger search? A test of Pillsbury's hypothesis. *Psychonomic Bulletin & Review*, *6*(3), 445–448.

Posner, M., & Cohen, Y. (1984). Components of visual orienting. *Attention and Performance X: Control of Language Processes*, *32*, 531.

Posner, M. I. (1980). Orienting of Attention. *Quarterly Journal of Experimental Psychology*, *32*(1), 3–25. https://doi.org/10.1080/00335558008248231

Pratt, J., Theeuwes, J., & Donk, M. (2007). Offsets and prioritizing the selection of new elements in search displays: More evidence for attentional capture in the preview effect. *Visual Cognition*, *15*(2), 133–148. https://doi.org/10.1080/13506280601029341

Sala, J. B., & Courtney, S. M. (2009). Flexible working memory representation of the relationship between an object and its location as revealed by interactions with attention. *Attention, Perception, & Psychophysics*, *71*(7), 1525–1533. https://doi.org/10.3758/APP.71.7.1525

Sander, M. C., Werkle-Bergner, M., & Lindenberger, U. (2011). Contralateral delay activity reveals life-span age differences in top-down modulation of working memory contents. *Cerebral Cortex*, *21*(12), 2809–2819.

Sawaki, R., Geng, J. J., & Luck, S. J. (2012). A Common Neural Mechanism for Preventing and Terminating the Allocation of Attention. *Journal of Neuroscience*, *32*(31), 10725–10736.

https://doi.org/10.1523/JNEUROSCI.1864-12.2012

Sawaki, Risa, & Luck, S. J. (2011). Active suppression of distractors that match the contents of visual working memory. *Visual Cognition*, *19*(7), 956–972. https://doi.org/10.1080/13506285.2011.603709

Schreij, D., Owens, C., & Theeuwes, J. (2008). Abrupt onsets capture attention independent of top-down control settings. *Perception & Psychophysics*, *70*(2), 208–218. https://doi.org/10.3758/PP.70.2.208

Shen, M., Tang, N., Wu, F., Shui, R., & Gao, Z. (2013). Robust object-based encoding in visual working memory. *Journal of Vision*, *13*(2), 1. https://doi.org/10.1167/13.2.1

Shiffrin, R. M. (1997). Attention, automatism, and consciousness. *Scientific Approaches to Consciousness*, 49–64.

Shih, S.-I., & Sperling, G. (1996). Is There Feature-Based Attentional Selection in Visual Search? *Journal of Experimental Psychology. Human Perception and Performance*, *22*, 758–779. https://doi.org/10.1037/0096-1523.22.3.758

Siebold, A., Van Zoest, W., & Donk, M. (2011). Oculomotor evidence for top-down control following the initial saccade. *PLoS One*, *6*(9).

Soto, D., Heinke, D., Humphreys, G. W., & Blanco, M. J. (2005). Early, involuntary top-down guidance of attention from working memory. *Journal of Experimental Psychology: Human Perception and Performance*, *31*(2), 248.

Soto, D., Hodsoll, J., Rotshtein, P., & Humphreys, G. W. (2008). Automatic guidance of attention from working memory. *Trends in Cognitive Sciences*, *12*(9), 342–348.

Soto, D., Humphreys, G. W., & Heinke, D. (2006). Working memory can guide popout search. *Vision Research*, *46*(6–7), 1010–1018.

Starc, M., Anticevic, A., & Repovš, G. (2017). Fine-grained versus categorical: Pupil size differentiates between strategies for spatial working memory performance. *Psychophysiology*, *54*(5), 724–735. https://doi.org/10.1111/psyp.12828

Theeuwes, J. (1994). Stimulus-driven capture and attentional set: Selective search for color and visual abrupt onsets. *Journal of Experimental Psychology. Human Perception and Performance*, *20*(4), 799–806. https://doi.org/10.1037//00961523.20.4.799

Theeuwes, Jan. (1989). Effects of location and form cuing on the allocation of attention in the visual field. *Acta Psychologica*, *72*(2), 177–192. https://doi.org/10.1016/0001-6918(89)90043-7

Theeuwes, Jan. (1991). Exogenous and endogenous control of attention: The effect of visual onsets and offsets. *Perception & Psychophysics*, *49*(1), 83–90. https://doi.org/10.3758/BF03211619

Theeuwes, Jan. (1992). Perceptual selectivity for color and form. *Perception & Psychophysics*, *51*(6), 599–606. https://doi.org/10.3758/BF03211656

Theeuwes, Jan. (1995). Abrupt luminance change pops out; abrupt color change does not. *Perception & Psychophysics*, *57*(5), 637–644. https://doi.org/10.3758/BF03213269

Theeuwes, Jan. (2010). Top–down and bottom–up control of visual selection. *Acta Psychologica*, *135*(2), 77–99. https://doi.org/10.1016/j.actpsy.2010.02.006

Theeuwes, Jan, & Burger, R. (1998). Attentional control during visual search: The effect of irrelevant singletons. *Journal of Experimental Psychology: Human Perception and Performance*, *24*(5), 1342.

Theeuwes, Jan, & Godijn, R. (2001). Attentional and oculomotor capture. *Attraction, Distraction and Action: Multiple Perspectives on Attentional Capture*, 121–149.

Theeuwes, Jan, & Godijn, R. (2002). Irrelevant singletons capture attention: Evidence from inhibition of return. *Perception & Psychophysics*, *64*(5), 764–770.

Theeuwes, Jan, Kramer, A. F., Hahn, S., Irwin, D. E., & Zelinsky, G. J. (1999). Influence of attentional capture on oculomotor control. *Journal of Experimental Psychology: Human Perception and Performance*, *25*(6), 1595.

Theeuwes, Jan, & Van der Burg, E. (2008). The Role of Spatial and Nonspatial Information in Visual Selection. *Journal of Experimental Psychology. Human*

Perception and Performance, *33*, 1335–1351. https://doi.org/10.1037/00961523.33.6.1335

Trappenberg, T. P., Dorris, M. C., Munoz, D. P., & Klein, R. M. (2001). A model of saccade initiation based on the competitive integration of exogenous and endogenous signals in the superior colliculus. *Journal of Cognitive Neuroscience*, *13*(2), 256–271.

Tsal, Y., & Lavie, N. (1988). Attending to color and shape: The special role of location in selective visual processing. *Perception & Psychophysics*, *44*(1), 15–21. https://doi.org/10.3758/BF03207469

Ueno, T., Allen, R. J., Baddeley, A. D., Hitch, G. J., & Saito, S. (2011). Disruption of visual feature binding in working memory. *Memory & Cognition*, *39*(1), 12–23.

van Zoest, W., & Donk, M. (2004). Bottom-up and top-down control in visual search. *Perception*, *33*(8), 927–937.

van Zoest, W., & Donk, M. (2005). The effects of salience on saccadic target selection. *Visual Cognition*, *12*(2), 353–375.

Van Zoest, W., & Donk, M. (2006). Saccadic target selection as a function of time. *Spatial Vision*, *19*(1), 61–76.

Van Zoest, W., & Donk, M. (2008). Goal-driven modulation as a function of time in saccadic target selection. *The Quarterly Journal of Experimental Psychology*, *61*(10), 1553–1572.

Van Zoest, W., Lleras, A., Kingstone, A., & Enns, J. T. (2007). In sight, out of mind: The role of eye movements in the rapid resumption of visual search. *Perception & Psychophysics*, *69*(7), 1204–1217.

Vierck, E., & Miller, J. (2005). Direct selection by color for visual encoding. *Perception & Psychophysics*, *67*(3), 483–494. https://doi.org/10.3758/BF03193326

Vogel, E. K., McCollough, A. W., & Machizawa, M. G. (2005). Neural measures reveal individual differences in controlling access to working memory. *Nature*, *438*(7067), 500–503.

Vogel, E. K., Woodman, G. F., & Luck, S. J. (2006). The time course of consolidation in visual working memory. *Journal of Experimental Psychology: Human Perception and Performance*, *32*(6), 1436.

Walker, R., Deubel, H., Schneider, W. X., & Findlay, J. M. (1997). Effect of Remote Distractors on Saccade Programming: Evidence for an Extended Fixation Zone. *Journal of Neurophysiology*, *78*(2), 1108–1119. https://doi.org/10.1152/jn.1997.78.2.1108

Wang, B., & Theeuwes, J. (2018). How to inhibit a distractor location? Statistical learning versus active, top-down suppression. *Attention, Perception, & Psychophysics*, *80*(4), 860–870. https://doi.org/10.3758/s13414-018-1493-z

Wang, C.-A., & Munoz, D. P. (2015). A circuit for pupil orienting responses: Implications for cognitive modulation of pupil size. *Current Opinion in Neurobiology*, *33*, 134–140. https://doi.org/10.1016/j.conb.2015.03.018

Watson, D. G., & Humphreys, G. W. (1997). Visual marking: Prioritizing selection for new objects by top-down attentional inhibition of old objects. *Psychological Review*, *104*(1), 90–122. https://doi.org/10.1037/0033-295x.104.1.90

Watson, P., Pearson, D., Chow, M., Theeuwes, J., Wiers, R. W., Most, S. B., & Le Pelley, M. E. (2019). Capture and Control: Working Memory Modulates Attentional Capture by Reward-Related Stimuli. *Psychological Science*, *30*(8), 1174–1185. https://doi.org/10.1177/0956797619855964

Wolfe, J. M. (1994). Guided search 2.0 a revised model of visual search. *Psychonomic Bulletin & Review*, *1*(2), 202–238.

Woodman, G. F., & Luck, S. J. (2007). Do the contents of visual working memory automatically influence attentional selection during visual search? *Journal of Experimental Psychology: Human Perception and Performance*, *33*(2), 363–377. https://doi.org/10.1037/0096-1523.33.2.363

Wright, R. D., & Ward, L. M. (2008). *Orienting of attention*. Oxford University Press.

Yantis, S. (1993). Stimulus-driven attentional capture and attentional control settings. *Journal of Experimental Psychology. Human Perception and Performance*, *19*(3), 676–681. https://doi.org/10.1037//0096-1523.19.3.676

Yantis, Steven. (2000). Goal-directed and stimulus-driven determinants of attentional control. *Attention and Performance*, *18*, 73–103.

Yantis, Steven, & Hillstrom, A. P. (1994). Stimulus-driven attentional capture: Evidence from equiluminant visual objects. *Journal of Experimental Psychology: Human Perception and Performance*, *20*(1), 95.

Yarbus, A. L. (1967). Eye Movements During Perception of Complex Objects. In A. L. Yarbus, *Eye Movements and Vision* (pp. 171–211). Springer US. https://doi.org/10.1007/978-1-4899-5379-7_8

Yu, Q., & Shim, W. M. (2017). Occipital, parietal, and frontal cortices selectively maintain task-relevant features of multi-feature objects in visual working memory. *Neuroimage*, *157*, 97–107.

Zhang, B., Zhang, J. X., Kong, L., Huang, S., Yue, Z., & Wang, S. (2010). Guidance of visual attention from working memory contents depends on stimulus attributes. *Neuroscience Letters*, *486*(3), 202–206. https://doi.org/10.1016/j.neulet.2010.09.052