What drives memory-based attentional capture? An investigation on category-based working memory guidance of visual attention

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By

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Abstract

Previous neurophysiological and behavioural studies have shown that attention can be guided by the contents of working memory (WM), and that such guidance can be involuntary even when it is detrimental to the task at hand. In three experiments, this thesis investigated whether the guidance of visual attention from WM could be generalized from a specific stimulus or a task to a category. Experiment 1 tested whether maintaining a set of stimuli of a specific category in WM would influence participants' deployment of visual attention to favour other stimuli that belonged to the same category. Experiment 2 further manipulated the interval between the onset of a critical prime (i.e., a stimulus in the same category as the stimuli held in WM) and the target to determine whether the results of Experiment 1 were associated with the lack of time for attention to be focused onto the critical prime. In both experiments, the stimuli held in WM never appeared in the prime display. In Experiment 3, the identity of the prime was manipulated so that it matched the stimuli held in WM on half of the trials. The results showed that when the stimuli held in WM never reappeared in the prime display (Experiments 1 and 2) there was no evidence that maintaining specific stimuli in WM biased the distribution of attention to other stimuli within the same category. However, when the stimuli held in WM could reappear in the prime display on some trials (Experiment 3), the participants whose reaction times were relatively fast showed evidence for category-based WM guidance of attention when the critical prime item was a new stimulus in the same category as the stimuli held in WM. In contrast, the participants whose reaction times were relatively slow showed a non-spatially specific

cost when the critical prime was one of the WM items than when it was a new item in the same category. These results showed that category-based WM could guide the deployment of visual attention under certain conditions. It further suggests that the relationship between WM and attention is more complex than what is outlined by the biased competition theory and related theories of attention.

Introduction

It has been widely accepted that humans can only process a certain amount of information at one time due to our limited cognitive capacity (e.g., Broadbent, 1958; Kahneman, 1973). Therefore, as the brain processes input information there is competition between stimuli as to which will be processed first. An influential model in this area is the biased competition model (Desimone & Duncan, 1995). According to this model such competition is resolved through interactions between bottom-up information and top-down knowledge. Bottom-up information such as stimulus salience and appearance of new objects captures attention in an involuntary fashion (see Theeuwes, 1991, 1992; Theeuwes & Burger, 1998; Yantis & Jonides, 1984). Top-down strategies and task relevancy also influence attention. Desimone and Duncan (1995) suggested that the guidance from working memory (WM) is one factor that influences attentional selection. In other words, what is currently held in a person's mind will to some extent affect what that person is attending to. The link between visual attention and WM can often be observed in day-to-day life. For example, if someone has mentally prepared a shopping list, he/she will likely find these listed items in the shop faster and more easily - suggesting that the distribution of visual attention is facilitated by the content of WM.

The concept of the guidance of attention by WM is supported by several lines of research. Behavioural studies have shown that the deployment of attention can be biased to a location occupied by the stimuli that match the content of WM (e.g., Downing, 2000; Soto, Heinke, Humphreys & Blanco, 2005; Soto, Humphreys & Heinke, 2006a, 2006b). Most studies on the relationship between WM and visual attention involve either searching for a target which matches or mismatches the item held in WM among several stimuli in a visual array (e.g., a visual search paradigm) or making a binary discriminatory judgment on a target at a location occupied previously by the item held in WM or by a new item (e.g., a spatial probe paradigm). In a typical experiment involving a visual search task, participants are first asked to remember an item (WM-item such as a colored shape). They then perform a visual search task (e.g., searching for a tilted line segment among upright distractor line segments) while holding the WM-item in mind. Finally, they perform a memory task. The general finding is that search was facilitated when the target was placed either inside the item or very close to the item held in WM. In contrast, when the item held in WM contained a distractor or was next to a distractor, search for the target was impaired (Olivers, Meijer, & Theeuwes, 2006; Soto, Heinke & Humphreys, 2005; Soto et al., 2006a, 2006b). These results suggest that attention was guided by the WM content. Importantly, even when a target never appeared inside the item held in WM, reaction times to the target were still slower when a distractor was inside the item held in WM relative to a neutral item (e.g., Olivers et al., 2006 and Soto et al., 2005), suggesting that attention was captured even when it was detrimental to the search task.

Converging evidence has also been obtained using a spatial probe paradigm. For example, in Downing (2000), participants were shown a face, which they held in WM prior to the appearance of a display that consisted of two faces. One of these faces matched the face held in WM, and the other face was new. A probe would then appear at the location of one of the faces in a subsequent display. The participants had to perform a probe discrimination task (i.e., a box with a gap at the top or at the bottom). The logic of Downing's study was that if attention was drawn to the face held in WM (despite being irrelevant to the probe discrimination task), participants would be faster to respond to the probe stimulus presented at the location of the matching face. This expected pattern of results was indeed obtained. Similar evidence was found in a number of other studies (e.g., Olivers et al., 2006; Solo et al., 2006a, 2006b).

There is also substantial neurophysiological and brain-imaging evidence for a close relationship between attention and working memory. It has been shown that two networks are involved in WM guidance of visual selection (see, Soto, Hodsoll, Rotshtein, & Humphreys, 2008 for a review). The first network is sensitive to the reappearance of the WM cue in the search display. When a match between the item in WM and the search display occurs, there is increased activity of neurons in the brain areas such as the superior frontal gyrus, mid-temporal and occipital areas that are known to be sensitive to prior history of events (Brown & Xiang, 1998; Chelazzi, Duncan, & Miller, 1998; Soto, Humphreys, & Rotshtein, 2007). Most importantly, depending on whether or not a task requires active maintenance of the item in WM, the neural responses are different. Soto et al. (2007) showed that when active maintenance was required, the re-appearance of the item in a subsequent search display enhanced activity in this brain network. By contrast, when the item was attended but not actively maintained, the same brain network showed decreased responses to the re-appearance of the cue in the search display. Biased Competition Theory suggests that this increased neural activity provides a competitive advantage for the matching stimuli, culminating in the capturing of attention.

The second network of areas involved in WM guidance of attention is the fronto-thalamic network (bilateral anterior prefrontal cortex and bilateral thalamic nuclei including the pulvinar). Neurons in these areas get activated most robustly when there is a match between the WM item and the search target (valid trials), and least robustly when there is a match between the WM item and a distractor (invalid trials) (Soto et al., 2007). This pattern of responses suggests that this network is sensitive to the congruency between internal (item held in WM) and external (visual information in the search array) signals based on their relevance for current behavioural goals.

As mentioned earlier, there is evidence that the content of WM can affect the deployment of visual attention even when the WM-item is associated with a distractor in the selective attention task (e.g., Soto & Humphreys, 2009; Soto et al., 2005, Soto et al., 2006a, 2006b). In terms of performance efficiency, if a WM-item is always associated with a distractor in the attention task, it should be beneficial for participants to ignore it. Attending to it will only cause interference, and therefore hinder (rather than help) performance. Thus, if participants are unable to ignore the WM-item, this would suggest that the guidance from WM can be triggered in an involuntary manner. Evidence for involuntary guidance by WM has been reported by several researchers (e.g., Olivers et al., 2006; Soto et al., 2005). For example, Solo et al. (2005, Experiment 4) showed participants target displays that consisted of simple geometric shapes, each containing either a tilted line or a vertical line. Before the target display was presented, participants saw a shape that they were required to hold in WM (e.g., a red square). The task was to search for a tilted line target among vertical line distractors. There were two experimental conditions. In one condition, a distractor was inside the shape that matched the WM-item (e.g., a vertical line inside a red square). In the other condition, the WM-item did not re-appear in the search display. Soto et al. (2005) found that reaction times (RTs) were slower in the former condition than in the latter condition even though the participants knew in advance that the coloured shape held in WM would never contain a target. Based on this and similar results, Soto et al. concluded that the increased distractor interference effect indicated that the WM guidance of attention was involuntary.

Previous research has also shown that WM can influence attentional selection based on semantic association (e.g., Chen & Tsou, 2011; Dark, Vochatzer, & Van Voorhis, 1996; Huang & Pashler, 2007; Moores, Laiti， & Chelazzi, 2003; Stolz, 1996, 1999). For example, Moores and her colleagues (Moores et al., 2003) found that searching for a target object (e.g., a chicken) was influenced by the presence of distractors which were semantically - but not visually - associated with the target (e.g., an egg). Specifically, when the target was absent, the presence of an associated object rendered search both slower and less accurate. Moreover, the initial saccades had a greater probability of landing on an associated item than on an unrelated distractor. According to the researchers, the activation of the target object representation in WM also activated the representations of the target-related objects, resulting in the capture of attention by these objects relative to neutral objects. In the absence of the target, the associated distractors attracted attention, and this, in turn, led to delayed and/or incorrect responses.

More recently, Chen and Tsou (2011) found evidence for a close link between task-related WM and visual attention. In one experiment (Experiment 2), participants were asked to memorize a task cue (in this instance either the “Shape” that referred to a shape discrimination task or the word “Gap” that referred to a gap location discrimination task) and then performed two tasks: a letter search task followed by an object identification task. In the search task, participants saw two geometric shapes in the search display, each containing a letter. One of the shapes was consistent with the task cue, and the other shape was inconsistent with the task cue. The target letter was equally likely to be inside the former (the consistent condition) or the latter (the inconsistent condition). In the object identification task, participants saw two objects: one related to the task cue, and the other unrelated. The task was to identify the object related to the task cue. For example, if the task cue was “Shape”, the task was to report the identity of the “Shape” object; whereas if the task cue was “Gap”, the task was to report the location of a gap on the “Gap” object. The principal manipulation in this experiment was the type of object the letter target was in (consistent vs. inconsistent with the task cue held in WM). The results showed that the RTs in the search task were slower on the consistent than inconsistent trials for the participants who had relatively slow reaction times. In contrast, the fast responding participants did not show such a task consistency effect. As the slow participants also showed a larger Stroop interference effect than the fast participants in a subsequent experiment, these results were taken as evidence for task-based WM on visual attention, at least for those participants who were inefficient in inhibiting the task irrelevant information. These results, together with the findings of Moores et al. (2003) and others (e.g., Dark et al., 1996; Huang & Pashler, 2007; Stolz, 1996, 1999), suggest that the effect of WM on attention does not depend on stimulus specificity. Instead, the deployment of visual attention to a stimulus can be influenced by the contents in WM when the stimulus and the content in WM are semantically related or when the two are linked by a specific task.

However, despite considerable evidence that WM contents capture attention, it should be noted that several studies have failed to find evidence of any WM effect on attention (e.g., Downing & Dodds, 2004; Houtkamp & Roelfsema, 2006; Woodman & Luck, 2007). These studies generally used a visual search paradigm. In a typical trial, participants were asked to remember two items, and then to search for a target in a search display which contained multiple distractors. Olivers (2009), after comparing the studies that did not find WM effects with those that did find WM effects, proposed that the inconsistent results were likely to be caused by the specific aspects of the task and the stimulus materials used in the different experiments. According to Olivers (2009), attentional capture effects may not be obvious or can be eliminated when search targets are not well-defined (Olivers, 2009, Experiment 6; Houtkamp & Roelfsema, 2006), or when the identity of a search target varies from trial to trial (e.g., Downing & Dodds, 2004; Houtkamp & Roelfsema, 2006; Olivers, 2009, Experiment 5). Furthermore, items in working memory may not show their effects on visual search when another item is more relevant or salient to the search task (Downing & Dodds, 2004; Houtkamp & Roelfsema, 2006; Olivers, 2009). For example, Houtkamp and Roelfsema (2006) found a WM effect in target-absent trials but not in target-present trials. This suggests that when the WM item had to compete with the search target for attention in target-present trials, the target won the competition as it was more relevant to the search task. Consequently, the WM item had little effect on visual search.

Moreover, Woodman and Luck (2007) found that, compared to unrelated distractors, a memory-matching distractor could reduce RTs rather than increased them. In their experiments (Experiments 3 and 4), participants were asked to remember one or three coloured boxes with a gap on one side of each box, after which they searched for another box with a gap at the top or bottom. The memorized item(s) could return as distractor(s). When the number of to-be-remembered boxes was three (i.e., in Experiment 3), the researchers found that visual search RT was faster on memory-matching distractor trials than on memory-mismatching distractor trials. Furthermore, increasing the number of memory-matching distractors led to faster search RTs (i.e., in Experiment 4). From these findings, they concluded that spatial attention might be directed away from the locations of memory-matching distractors to prevent irrelevant visual information from causing interference, resulting in more efficient search. Woodman and Luck (2007) further suggested that when the content in WM was known to be irrelevant to the current task goal, it could be shielded from the relevant task at hand. Converging evidence was reported by Koelewijn, Van der Burg, Bronkhorst and Theeuwes (2008), who also found that objects that were irrelevant to the current task were inhibited, resulting in impaired detection when the same object happened to return as a target.

In summary, there is currently mixed evidence on whether the contents of WM guide attention involuntarily. Although many studies have found evidence for memory-driven attentional capture (e.g., Olivers et al., 2006; Soto et al., 2005, 2006b), other studies, using comparable procedures, have failed to find such attentional capture effects or memory-driven inhibition (e.g., Downing & Dodds, 2004; Houtkamp & Roelfsema, 2006; Woodman& Luck, 2007). In the experiments reported in this thesis, I sought to extend prior research by determining whether items held in WM would bias the deployment of visual attention in a display when one of the stimuli in the display was in the same category as those held in WM.

The Present Study

The present study investigates category-based WM effect on the guidance of visual attention. Objects that belong to the same category typically share many properties, such as physical appearance and/or function. Given the findings from previous studies (e.g., Chen & Tsou, 2011; Moores et al., 2003), it is possible that the activation of objects in WM could spread to items within the same category, and this in turn could lead to the guidance of visual attention. While in everyday life people often keep specific items in mind, they also keep a specific category in mind. For example, a person may be thinking of buying some instant noodles in the grocery store, without having any specific type or brand in mind. The present study examines this category-based WM effect on attention using a spatial probe paradigm as shown in Figure 1 below.

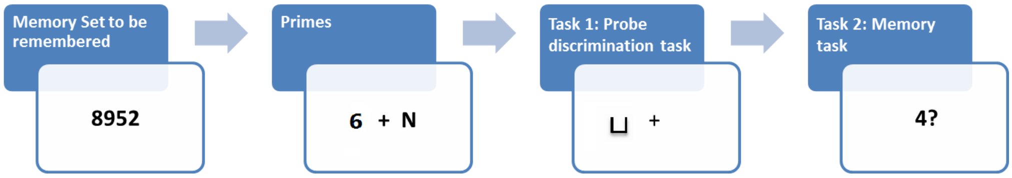

Figure 1. A schematic representation of the spatial probe paradigm used in the present study.

In all the three experiments reported in this thesis, participants performed two tasks in each trial: a gap discrimination task and a memory task. Participants were required to remember a memory set at the beginning of each trial (either four digits or four letters). While the memory set was held in WM, two primes were presented simultaneously and briefly. One of these primes belonged to the same category as the memory set (the same-category prime), and the other belonged to a different category (the different-category prime). Participants then performed a gap discrimination task in which they indicated whether the gap in a rectangle occurred at the top or bottom. The critical manipulation was the location of the rectangle: it was equally likely to occur either near (at or directly below) the location of the preceding same-category prime or near the location of the different-category prime. If items that belonged to the same category as those held in WM could attract attention involuntarily, participants would be faster to respond in the gap discrimination task when the rectangle appeared in a location that was nearer to that occupied by the same rather than different category prime on the previous display. Finding positive evidence would support the notion of automatic attentional guidance by WM, and that this WM guidance effect could be extended beyond the current memory set to related stimuli outside the current memory set but within the same category as that held in WM.

Three experiments were carried out in the present study. Experiment 1 manipulated the category of a critical prime item: it was equally likely to be a stimulus from the same category as the items held in WM or a stimulus in a different category. Experiment 2 varied the stimulus onset asynchrony (SOA) between the prime and target displays in addition to the manipulation of the prime category. In both Experiments 1 and 2, the identity of the critical prime always differed from that of the stimuli held in WM regardless of whether they belonged to the same category. In Experiment 3, the identity of the critical prime item was further manipulated when it was a stimulus from the same category as that held in WM: the prime was identical to one of the items held in WM on half of the trials and it was a new item in the same category on the remaining trials. Together, these experiments investigated whether or not maintaining a specific category (e.g., number or letter) in WM would influence participants' deployment of visual attention to favour stimuli in that category.

Experiment 1

Experiment 1 was designed to investigate whether an item belonging to the same category as items held in WM (but not identical to these WM items) could guide attention involuntarily. Participants performed two tasks in each trial: a speeded gap discrimination task, and an accuracy-only memory task. The principal manipulation was the location of the target rectangle relative to the two prime stimuli (a letter and a number) presented before the onset of the target rectangle. The rectangle was shown either at the location of the preceding prime stimulus in the same category as the items held in WM or at the location of the other stimulus. From hereon, the prime in the same category as the items held in the WM will be termed the “working memory category matching item”, or “WMC-matching item”, as an abbreviation. Of particular interest was whether participants’ RTs in the gap discrimination task would differ as a function of the congruency of the locations between the WMC-matching item and the target.

Method

Participants. Eleven students were recruited, either through advertising around the campus of the University of Canterbury or from the participant pool of introductory psychology courses. There were eight females and three males. They were aged between 18 and 46, and their vision (self-reported) was normal or corrected-to-normal. Depending on whether or not participation was part of a course requirement, either course credit or a voucher for petrol or groceries (worth $10) was given in return for participation.

Apparatus and Stimuli. All stimuli presented were black against a white background, and were displayed on a computer with a 16in. CRT colour monitor with a refreshing rate of 60hz. Participants were seated approximately 60cm from the screen, and entered responses via a computer keyboard. The experiment was programmed through

E-prime (Schneider, Eschman, & Zuccolotto, 2002). Responses were also collected through E-prime. Participants were tested individually in a low-light environment.

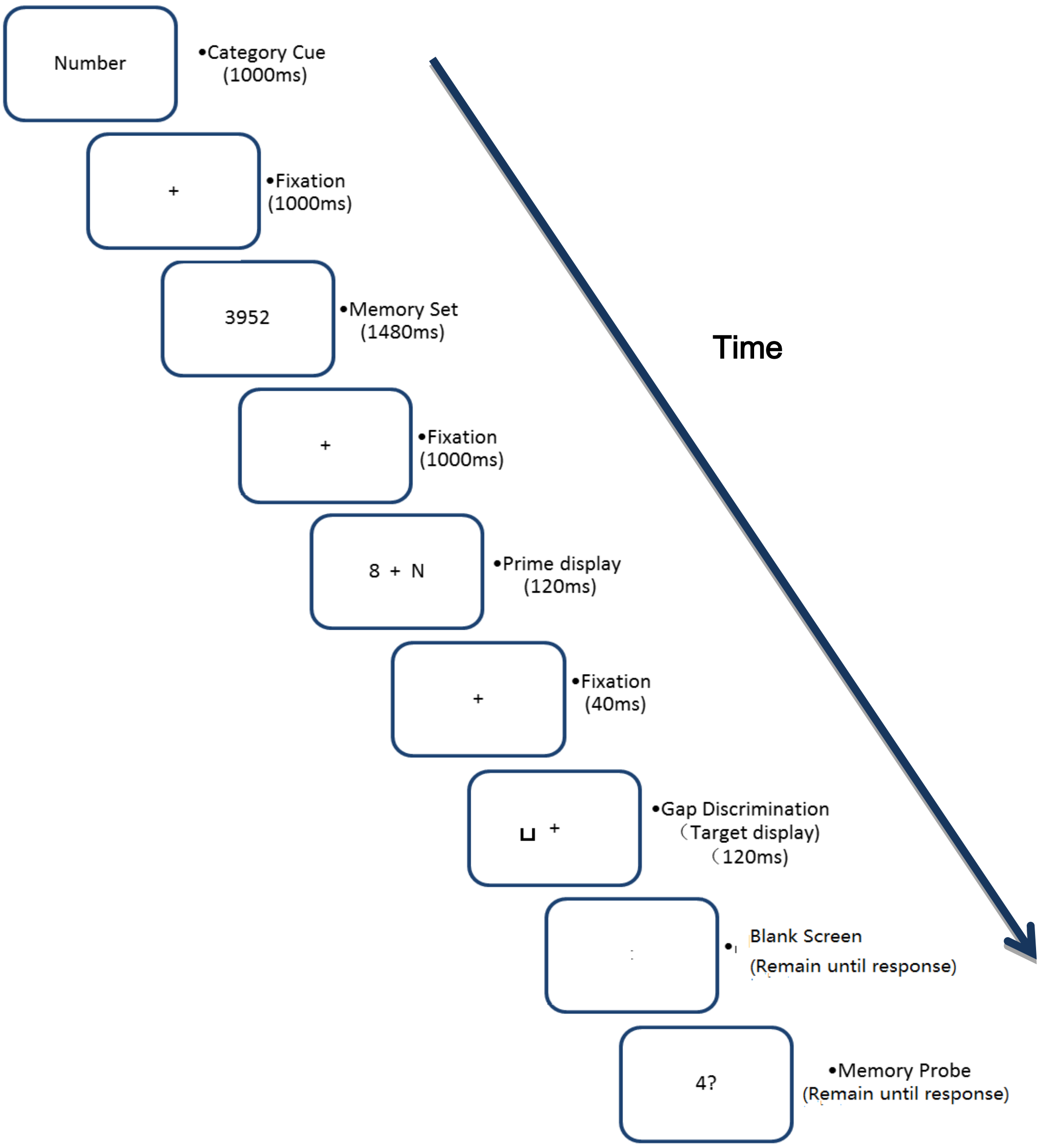

Figure 2: A schematic illustration of a trial in the same condition in Experiment 1.

The event sequence of a sample trial is shown in Figure 2. Each trial consisted of a series of displays: a category cue, a memory set, a prime display, a gap discrimination target, and a memory probe. The category cue, which was presented in the centre of the screen, was a word (“Number” or “Letter”) written in bold 18-point Courier New font. The memory set, which was also presented in the centre of the screen and was written in bold 24-point Courier New font, contained either four numbers randomly selected from 1 to 9, or four letters randomly selected from A to Z, excluding O (which was excluded due to its similarity to the number “0”). The prime display consisted of three items: a number, a central fixation, and a letter. The number and the letter, which were also written in 24-point Courier New font, were located 4.68° to the left and right of fixation, with their positions counterbalanced across trials. The fixation was a small black cross of 0.38°. The gap discrimination display consisted of a target and the fixation mentioned above. The target, which was 0.48° in both length and width, was a rectangle with a gap at either the top or the bottom. The rectangle appeared on either the left or right side of the screen with equal frequency, at the location previously occupied by the letter or the number. The memory probe consisted of either a letter or a number appearing at the centre of the screen with a question mark beside it. The participants were encouraged to perform well in both the gap discrimination and the memory tasks.

Design and Procedure. Experiment 1 used a within-subjects design, with the principal manipulation being the congruency of the locations between the WMC-matching item and the target, which was presented at either the same location as (the same condition), or a different location from (the different condition), the location previously occupied by the WMC-matching item. The congruency of the locations was randomized, with equal probability within each block. Participants initiated the experiment by pressing the space bar. Then, a category cue of either the word

“Number” or “Letter” was shown with equal frequency for 1000ms, followed by a 1000ms fixation. Upon the latter's offset, the memory items appeared. They stayed on the screen for 1480ms. Depending on the category cue, the memory items were either digits or letters (i.e., if the task cue was “Number”, four digits would appear; likewise, if the task cue was “Letter”, four letters would appear). Participants were instructed to memorize the items. After the offset of the memory items, the fixation display returned for another 1000ms. This was followed by the prime display for 120ms. In half of the trials, the number in the display was to the left of the fixation; in the remainder, it appeared to the right of the fixation. The same was true for the location of the letter. The participants were told that neither the number nor the letter in the prime display would come from the memory items. After the offset of the prime display, there was again a fixation display of 40ms. Next, the target for the gap discrimination task appeared. The gap was at the top of the rectangle (“gap up”) in half the trials and at its bottom (“gap down”) in the other half. The target was presented for 120ms, followed by a blank screen. In the gap discrimination task, the participants used their right hand to press the “.” key if the response was “gap up”, and the “/” key if it was “gap down”. The response to the target terminated the blank screen and triggered the memory probe. Participants then judged whether the number or the letter in the memory probe display was one of the items in the memory set. The memory probe was a stimulus in the memory set in half of the trials, and it was a new stimulus in the other half of the trials. The participants used their left hand to press either the “z” or “x” key in accordance with a "yes" or a "no" response, respectively. Once they pressed a response key the next trial was initiated. They were informed that only accuracy would be measured in the memory task, and they were asked to respond as accurately and as quickly as possible in the gap discrimination task. The experiment consisted of 4 blocks of 64 trials, preceded by 2 blocks of 12 practice trials. The entire experiment took approximately 50 minutes to complete.

Results and Discussion

Gap discrimination RTs those were longer than 2000ms were removed. The percentage of the data removed in Experiment 1 is 0.64%. In addition, data from one participant were excluded from analysis in Experiment 1 because his/her gap detection response times were 5 standard deviations longer than the mean response time of the other participants. The accuracy of the memory task was high, with an average of 91.3% correct responses. Only trials that were correct in both the memory probe task and the gap discrimination task were included in the gap discrimination RT analysis below.

The main focus of the study was performance on the gap discrimination task. Two t-tests for dependent means were conducted, one on the mean RTs and the other on the accuracy data. The results showed that the RTs were comparable for the same (598ms) and the different condition (594ms), $t(9) = -1.01$, $p = 0.34$. The difference in accuracy between these two conditions also failed to reach significance, with a 5.1% error rate in the same condition and a 5.4% error rate in the different condition, $t(9) = 0.58$, $p = 0.58$.

No significant results in either RT or accuracy were found in Experiment 1. Thus, there was no evidence that attention was involuntarily captured by items that matched the category of the items being held in working memory, at least in the present paradigm. Inspection of the experimental design raised the possibility that one or more of the following factors might account for the null results. First, there might not be sufficient time for the manifestation of an attentional effect. As the location of the target could be on either side of the fixation in the target display, it would not be particularly helpful to allocate attention to a particular location in advance (Watson, Humphreys & Olivers, 2003). As a result, the participants might adopt the strategy maintaining a wide attentional extent that incorporated both target locations. Due to the short time interval of 160ms between the onset of the prime display and the onset of the target, the participants might not have enough time to narrow their attentional focus to the location of the WMC-matching item before the onset of the target. This may have prevented an attentional effect from manifesting in Experiment 1.

A second possibility is that the participants might have tried to inhibit all the items that were irrelevant to their behavioural goals on a particular trial. For example, if the items to be remembered were “3952” on a number trial, the participants might try to inhibit all the non-presented numbers in the number category together with all the letters. Because the prime display consisted of only those stimuli not presented in the memory set, if they were inhibited to the same degree, this could lead to the null results found in Experiment 1.

Another factor that might affect the pattern of the result in Experiment 1 is the amount of time necessary for cognitive control to become effective. Han and Kim

(2009, Experiment 4) showed that when a WM matching item was associated only with distractors, whether WM guidance of attention was found depended on the duration of the place-holders for the stimuli in the search display before the onset of the target display (the latter contained the WM-item on some of the trials). Evidence for the WM guidance of attention was found when the interval was short (i.e., 150ms), but not when it was long (i.e., 750ms). Moreover, when it was long, there was evidence that the memory-matching distractor was inhibited. In this latter case, participants appeared to be biased against selecting the WM-matching item, facilitating the selection of the target in those displays that contained the WM-matching item compared with the displays that did not. Presumably, the long presentation duration of the place-holders before the onset of the target provided the participants with sufficient time to initiate cognitive control, which eliminated the effect of attentional capture by WM. Although the many differences between Han and Kim's experiment and the present experiment make it impossible to draw any definitive conclusion, the results of Han and Kim's study suggest that the operation of cognitive control processes takes time to be implemented.

In the next two experiments, I explored the factors mentioned above. In Experiment 2, the delay between the onset of the prime and that of the target display (stimulus-onset asynchrony; SOA) was manipulated. The goal was to determine whether providing participants with sufficient time to narrow their attentional focus to the location of the WMC-matching item would allow the effect of WM guidance on attention to manifest.

Experiment 2

Experiment 2 was designed to test the possibility that the brief prime-target SOA used in Experiment 1 might have prevented the manifestation of the attentional effect. In Experiment 2, three SOAs were used. The specific SOAs selected for the experiment were based partly on Han and Kim (2009) that I described earlier and partly on research that used the “inhibition of return” paradigm (Posner & Cohen, 1984).

It has been hypothesized since Wundt (1897, p. 219) that there are at least two ways of allocating spatial attention, i.e., voluntarily and involuntarily. Voluntary and involuntary attentions differ in many aspects (see, e.g., Jonides, 1981; Juola, Koshino, & Warner, 1995; Müller & Rabbitt, 1989; Posner, Cohen, & Rafal, 1982; Spence & Driver, 1994; Warner, Juola, & Koshino, 1990). For example, Prinzmetal, Park and Garrett (2005) showed that involuntary and voluntary attention differed in their time course. Whereas involuntary attention has its maximum effect with short cue–target SOAs (i.e., 70-150 ms, Nakayama & Mackeben, 1989), voluntary attention has its maximum effect at longer SOAs. Furthermore, with involuntary attention participants are typically slower on valid trials (i.e., trials where target appears at/near the cued location) than on invalid trials (i.e., trials where target appears away from/opposite from the cued location) when SOAs are relatively long (e.g., Maylor, 1985; Nakayama & Mackeben, 1989; Posner & Cohen, 1984). For example, in average, if the target appeared with a delay of 300ms or more after a valid cue, target discrimination was slowed down as compared to when the SOA between cue and target was shorter than 300ms. The usual effect of facilitation when the cue-target delay is short is thus reversed and becomes an inhibitory effect when the cue-target delay is long. This latter effect is called *inhibition of return* (IOR). IOR occurs only with involuntary attention and does not occur with voluntary attention (Posner & Cohen, 1984; Richard, Wright, & Ward, 2003).

In addition to the difference in time course (Berger, Henik & Rafal, 2005; Briand & Klein, 1987; Jonides, 1981; Müller & Rabbitt, 1989), voluntary and involuntary attention is also summoned differently. Voluntary attention is goal-directed (endogenous). Observers voluntarily allocate attention to the spatial location that may contain information that is important or relevant to the immediate task goal. Involuntary attention is stimulus-driven (exogenous). Stimuli can capture attention even when they are unrelated to the current goal-related task. If the contents of WM guide attention in an involuntary manner, varying the SOA between the prime and target in the present paradigm could potentially provide participants with more opportunities to show evidence of category-based working memory effect on attention. In consideration of these factors, three SOAs (i.e., 200ms, 400ms and 640ms) were used in Experiment 2. It was hoped that introducing different SOAs would aid in revealing the effects of working memory on visual attention, and perhaps also shed some light on the cause of the null results of Experiment 1.

Method

Participants. Twenty-three new participants, fifteen females and eight males, took part in this experiment. All were aged between 18 and 36 years and had vision that was normal or corrected-to-normal. Course credits or $10 vouches were given in return for participation.

Apparatus and Stimuli. These were the same as those used in Experiment 1.

Design and Procedure. Experiment 2 differed from Experiment 1 in three aspects. Firstly, the SOA between the prime and target displays was manipulated. Trials with SOAs of 200ms, 400ms and 640ms were equiprobable and were randomised within each block. Secondly, the duration of the prime display was extended from 120ms to 160ms. Finally, the target was displaced slightly downward in Experiment 2 as compared to Experiment 1. It was located at 0.5^0 below the horizontal meridian. This was done to minimize the possibility of the critical prime and the target being integrated (Breitmeyer, 1984) and to reduce the possibility of forward masking of the target by the prime. Thus, Experiment 2 used a 2x3 within-subjects design. The principal manipulations were the congruency of the locations between the WMC-matching item and the target (congruent vs. incongruent), and the prime-target SOA (i.e., 200ms, 400ms and 640ms). All the other aspects of Experiment 2 were identical to those of Experiment 1.

Results and Discussion

The accuracy of the memory task was high, with an average of 95.11% of responses being correct. As in Experiment 1, only those trials that were correct on both the memory probe task and the gap discrimination task were included in the RT analysis for the gap discrimination task. Again, gap discrimination RTs longer than 2000ms were removed, and these trials constituted 0.27% of the data.

Table 1

Mean Reaction Times and Error Rates (Percentage Error), with Standard Errors (SE), for the Target Discrimination Task in Experiment 2.

	Short SOA				Median SOA				Long SOA			
	Congruent		Incongruent		Congruent		Incongruent		Congruent		Incongruent	
	M	SE	M	SE	M	SE	M	SE	M	SE	M	SE
RT (ms)	618	25	621	25	570	24	565	23	569	23	574	24
% Error	*5.11*	*0.98*	*3.95*	*0.63*	*3.72*	*0.80*	*3.09*	*0.60*	*1.99*	*0.45*	*2.48*	*0.66*

Table 1 shows the mean RTs and percentage error. A 2x3 repeated-measures analysis of variance (ANOVA) was carried out on the mean RTs in the gap discrimination task, with congruency and SOA as factors. The effect of congruency was not significant. The mean RT was 586ms in the congruent condition and 587ms in the incongruent condition, F (1, 22) = 0.27, p = 0.61. Not surprisingly, there was a significant effect of SOA , F(2, 44) = 63.14, p < .005. Tukey's Honestly Significant Difference (HSD) test further indicated slower RTs in the short SOA condition (620 ms) than in both the medium (567ms) and long (572ms) SOA conditions (p = .0001 in both cases). There was no significant difference between the medium and long SOA conditions (p = 0.69). The SOA effect presumably reflected the fact that the participants were better prepared for target processing when the prime-target SOA was relatively long. The interaction between congruency and SOA was not significant, F (2, 44) = 0.67, p = 0.50.

Consistent with the RT results, an ANOVA on accuracy data showed no effect of congruency. The average error rates were 3.61% in the congruent condition and 3.17% in the incongruent condition, F (1, 22) = 0.65, p = 0.43. The effect of SOA was again significant (4.53% in the short SOA condition, 3.40% in the median SOA condition and 2.21% in the long SOA condition), F (2, 44) = 7.11, p < .005. Tukey's HSD test further indicated higher accuracy in the long SOA condition than in the short SOA condition (p = .001). There was no significant difference between the medium and long conditions (p = 0.14), or between the short and medium conditions (p = 0.17). No interaction effect was found between congruency and SOA, F (2, 44) = 1.53, p = 0.23. There was no indication of a trade-off between speed and accuracy.

Experiment 2 extended the prime and target SOA to 600ms. Yet, there was still no evidence for category-based WM guidance of attention. This suggests that the null result of Experiment 1 was not due to a lack of time for the WM effect to manifest.

Experiment 3

In both Experiments 1 and 2, the items held in WM never appeared in the prime display. This was to ensure that participants had no incentive to pay special attention to the prime items, thereby minimizing the possibility that the participants engaged in perceptual resampling during the prime display (Woodman & Luck, 2007). Perceptual resampling is a term coined by Woodman and Luck (2007), who pointed out that it is possible that the participants in some previous experiments may have been motivated to allocate attention to the items that matched the contents of WM in a search display due to the specific design of these experiments (e.g., Downing, 2000; Pashler & Shiu, 1999). For example, in Downing's (2000) study, although the two faces that appeared in the search display were supposed to be irrelevant to the probe task, it was possible that observers allocated some attention to the matching face during the search task because one of the faces always matched the face held in WM and the participants knew that their memory for the face held in WM would be tested immediately after the search task. If the participants adopted the strategy of perceptual resampling, this could result in more attention being allocated to the location of the WM-matching item, resulting in faster responses to the target at that location.

Experiments 1 and 2 in the present study were designed to eliminate incentives to pay any attention at all to the primes and thereby to discourage perceptual resampling. However, because neither the number nor the letter stimuli provided any information about the target, the participants might wisely inhibit all the stimuli temporarily including those present in the memory set in order to reduce potential interference in the target discrimination task. If that was the case, then any effect of the content in WM would be very minimal in Experiment 1 and 2, consistent with the numerous studies which demonstrate that the relationship between the content in WM and visual attention may be stimuli-specific. That is only the specific stimulus currently in WM will guide the allocation of visual attention. Therefore, in order to observe the possible effect of a specific stimulus category held in WM on attention, the experimental design should prevent participants from suppressing the WM content. If the WM items could appear on the prime display in an appropriate proportion of trials (i.e., not so large as to encourage perceptual sampling), the participants might be less motivated to inhibit all the numbers and letters and hence prevent them from blocking out the numbers or letters presented in the memory set. To test this possibility, in Experiment 3, the WM items could appear in the prime display in half of the trials. The main question of the experiment was whether the effect of WM on attention would be observed on these trials.

Method

Participants. Twenty-four new participants, with twenty females and four males, took part in this experiment. All were aged between 18 and 34 years and all had vision that was normal or corrected-to-normal. As before, either course credit or a voucher valued $10 was given in return for participation.

Apparatus and Stimuli. They were the same as those in Experiment 1.

Design and Procedure. They were the same as those in Experiment 2, except for the differences listed below. First, only two SOAs (short SOA: 200ms and long SOA: 640ms) were used. Second, on half of the trials the critical prime item was identical to one of the WM items (i.e., the prime ID same condition), and on the other half of the trials it did not match any of the four WM items, although it was still in the same category as the stimuli in the memory set (i.e., the prime ID different condition). Because there were 4 items in the memory set, each item would appear as a critical prime on 12.5% of the trials and as a memory probe on 6.25% of the trials.

As a result, the design of Experiment 3 was a $2 \times 2 \times 2$ within-subjects design. The three factors were: the congruency of locations (congruent vs. incongruent), the identity of the critical prime (prime ID same vs. prime ID different) and the prime-target SOA (short SOA vs. long SOA). These three factors were varied orthogonally within each block. The experiment again consisted of 4 blocks of 64 trials. Prior to the experimental trials there were 2 blocks of 16 practice trials. All the other aspects of the experiment were identical to those of Experiment 1.

Results and Discussion

Accuracy in the memory task was again high, with an average of 95.16% correct responses. As in the previous experiments, only those trials that were correct on memory probe task were included in further analyses, and RTs longer than 2000ms, which constituted 0.16% of the data, were removed. Table 2 shows the mean RTs and percentage error for the gap discrimination task.

A 2×2×2 repeated-measures ANOVA on the mean RT data from the gap discrimination task showed that the participants were slower when the SOA was short (563ms) than when it was long (528ms), $F(1, 23) = 21.01$, $p < .01$. In addition, they were also slower when the critical prime item was one of the WM items (550ms) as compared to when it was a new item (540ms), $F(1, 23) = 9.76$, $p < .005$. Once again, there was neither a significant difference between the congruent (586ms) and incongruent（587ms） conditions, $F(1, 23) < 1$, *ns*, nor a significant Prime ID by congruency interaction, $F(1, 23) < 1$, *ns* No other effects were significant in the RT analysis.

Table 2

Mean Reaction Times and Error Rates (Percentage Error), with Standard Errors, for Target Discrimination Task in Experiment 3.

Short SOA								
Prime ID	Same				Different			
Location	Congruent		Incongruent		Congruent		Incongruent	
	M	SE	M	SE	M	SE	M	SE
RT (ms)	566	23	570	25	559	20	558	21
% Error	*5.26*	*1.15*	*4.02*	*0.91*	*4.45*	*1.10*	*5.89*	*1.26*
Long SOA								
Prime ID	Same				Different			
Location	Congruent		Incongruent		Congruent		Incongruent	
	M	SE	M	SE	M	SE	M	SE
RT (ms)	536	21	530	18	524	20	521	21
% Error	*5.11*	*0.98*	*3.72*	*0.80*	*3.95*	*0.63*	*3.09*	*0.60*

Analysis of the accuracy data showed that the participants made more errors when the SOA was short (4.9% error rate) than when it was long (3.3% error rate), $F(1, 23) = 4.93$, $p < .05$. The effect of congruency was close to significance, $F(1, 23) = 3.61$, $p = .07$, suggesting fewer errors in the congruent condition (3.76% error rate) than in the incongruent condition （4.44% error rate）. No other effects reached significance.

Visual inspection of the data indicated that the participants whose responses were relatively fast showed a different pattern of data from those participants whose responses were relatively slow. Previous research (e.g., Chen & Tsou, 2011; Han & Kim, 2009) has also found different patterns of data between the fast and slow participants. In one of their experiments, Han and Kim divided their participants into two groups (Fast vs. Slow search group) based on their RTs in a neutral condition (i.e., the visual search display did not contain the WM-item), and found that the two groups showed different WM effects. Those participants from the fast search group showed a marginally significant attentional capture effect by WM, while the slow search group showed “a negative bias against” stimuli that matched the WM content (Han & Kim, 2009, p 1295). As described previously, Chen and Tsou (2011) also reported different patterns of WM effect on attention for fast and slow participants, and they provided evidence in a separate experiment that the slow participants also showed a larger Stroop interference effect than the fast ones. These results suggest that the effect of WM on attention may differ as a function of participants’ ability to inhibit irrelevant information (Chen & Tsou, 2011).

In order to have a better understanding of the different pattern of data between the fast and slow participants in the present experiment, the participants were split into two groups according to their mean RTs. The fastest half of them was assigned to the fast response group, and the other half to the slow response group (see Table 3).

Table 3

Mean Reaction Times and Error Rates (Percentage Error), with Standard Errors, for the Slow and Fast Groups in the Target Discrimination Task in Experiment 3.

Short SOA condition

	Fast Group				Slow Group			
	Prime ID same							
Location	*Congruent*		*Incongruent*		*Congruent*		*Incongruent*	
	M	SE	M	SE	M	SE	M	SE
RT	492	13	498	14	641	32	641	39
%Error	*5.56*	*1.70*	*4.42*	*1.63*	*4.86*	*1.61*	*3.63*	*0.88*
	Prime ID different							
RT	501	15	489	16	618	29	627	28
%Error	*5.67*	*1.88*	*7.96*	*2.06*	*3.22*	*1.11*	*3.83*	*1.28*

Long SOA condition

	Fast Group				Slow Group			
	Prime ID same							
Location	*Congruent*		*Incongruent*		*Congruent*		*Incongruent*	
	M	SE	M	SE	M	SE	M	SE
RT	468	9	466	9	604	30	594	24
%Error	*3.79*	*1.27*	*5.25*	*2.10*	*3.05*	*1.39*	*3.05*	*1.05*
	Prime ID different							
RT	463	14	445	7	584	30	597	27
%Error	*2.79*	*1.47*	*4.90*	*2.14*	*1.06*	*0.59*	*2.50*	*0.92*

A 2×2×2×2 mixed ANOVA on RTs with group as a between-subject factor was carried out. Four significant results were found. Consistent with the results from the previous analyses, the main effects of SOA and prime ID remained significant, $F(1, 22) = 20.12$, $p < .001$ for SOA, and $F(1, 22) = 9.84$, $p < .01$ for prime ID. As expected, there was also a significant effect of group, $F(1, 22) = 20.06$, $p < .001$, with faster responses for the fast group (478ms) than for the slow group (613ms). In addition, there was a significant three-way interaction of prime ID, congruency, and group, $F(1, 22) = 5.79$, $p<.05$. To clarify this interaction, the data for the two groups were analysed separately.

For the fast group, a 2×2×2 repeated-measures ANOVA showed that responses were again slower in the short SOA condition (495ms) than in the long SOA condition (461ms), $F(1, 11) = 16.98$, $p < .001$. In addition, there was a significant interaction between prime ID and congruency, $F(1, 11) = 4.93$, $p < .05$. When the prime was a new stimulus, the RT was longer in the congruent condition (482ms) compared to the incongruent condition (467ms). No such congruency effect was found when the prime item matched one of the WM items (RT = 480ms and 482ms for the congruent and incongruent conditions, respectively). No other effects reached significance.

A similar analysis was conducted on the accuracy data. The only significant effect was a main effect of congruency, suggesting higher accuracy in the congruent condition (4.47% of error rate) than in the incongruent condition (5.63% of error rate), $F(1, 11) = 4.87$, $p < .05$. No other effects were significant.

The same analyses were also carried out for the slow group. In RT, both the main effects of SOA and prime ID were significant. The participants were slower in the short SOA condition (632ms) than in the long SOA condition (595ms), $F(1, 11) = 7.44$, $p < .01$. They were also slower when the critical prime item matched the WM item（RT = 620ms）than when it did not match (RT = 606ms), $F(1, 11) = 6.06$, $p < .05$. Unlike the results in the fast group, there was no significant interaction between prime ID and congruency, $F(1, 11) = 1.95$, $p = .19$. No other effects reached significance.

A similar analysis was conducted on the accuracy data. The main effect of prime ID was marginally significant, $F(1, 11) = 4.77$, $p = .051$, with a higher error rate in the prime ID same condition (3.65%) than in the prime ID different condition (2.65%). No other significant results were found.

The most interesting finding of Experiment 3 was that the participants with relatively fast and slow RTs showed different patterns of data. For the slow group, RT was slower when the critical prime item matched one of the WM items than when it was a new stimulus in the same category. However, the same prime ID effect was found only in the incongruent condition in the fast group. How can we explain this pattern of data?

For the slow group (see Figure 3a), RT was longer in the prime-ID same condition than in the prime-ID different condition. This suggests that when a WM-matching item re-appeared in the prime display, it was activated more strongly than a stimulus not held in WM, and this stronger activation could make attention more difficult to disengage, resulting in longer RTs to the target in the subsequent display in the prime-ID same than prime-ID different condition.

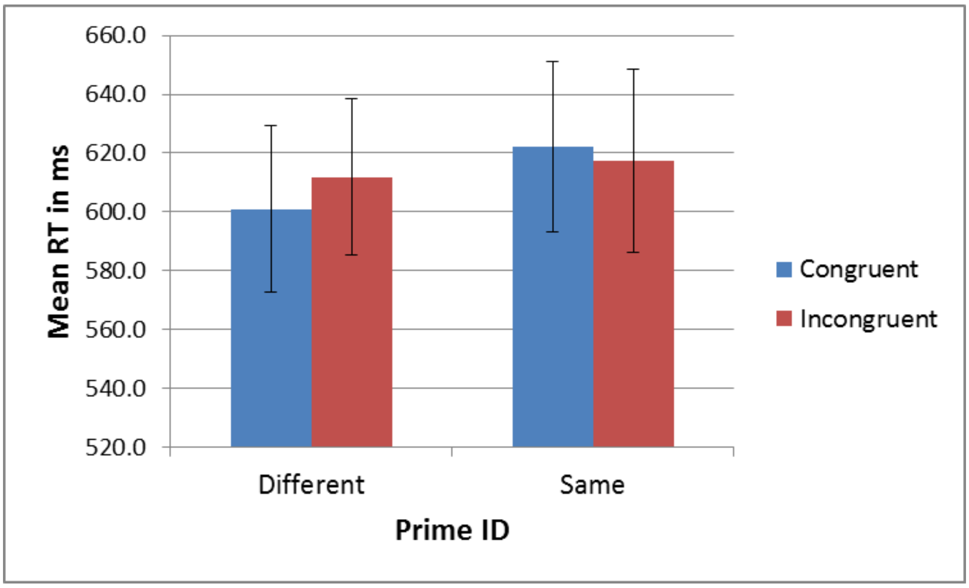

Figure 3a: Mean RTs as a function of Prime ID and Congruency collapsed across the short and long SOA conditions for the slow group in Experiment 3.

Interestingly, the specific location of the target relative to the critical prime did not affect the response latencies of the target, suggesting that the WM effect on attention was non-spatially specific. Although it is unclear why a location-specific effect was not found, a similar result was reported by Moores et al. (2003), whose participants showed WM guidance on attention in a non-spatially specific way too. Their participants saw search displays that consisted of 4 objects followed by a small probe in the center of one of the objects. The task was to indicate the location of the probe (left or right side of the screen) as quickly as possible before responding to the search target, which could be present or absent in the search display. The probe could be at the location of the target or at the location of a distractor. In the latter case, it could be an object related or unrelated to the target. The results showed that the RT to the probe was slower when the search display included a search target compared with when the search display consisted of only distractors. Furthermore, the location of the probe relative to the search target (i.e., whether it was at the location of the target or not) had negligible effect on the probe RTs. Thus, in both Moores et al. (2003) and the present experiment, participants showed a non-spatially specific cost when a display included an item related to the content in WM relative to when a display did not include such an item.

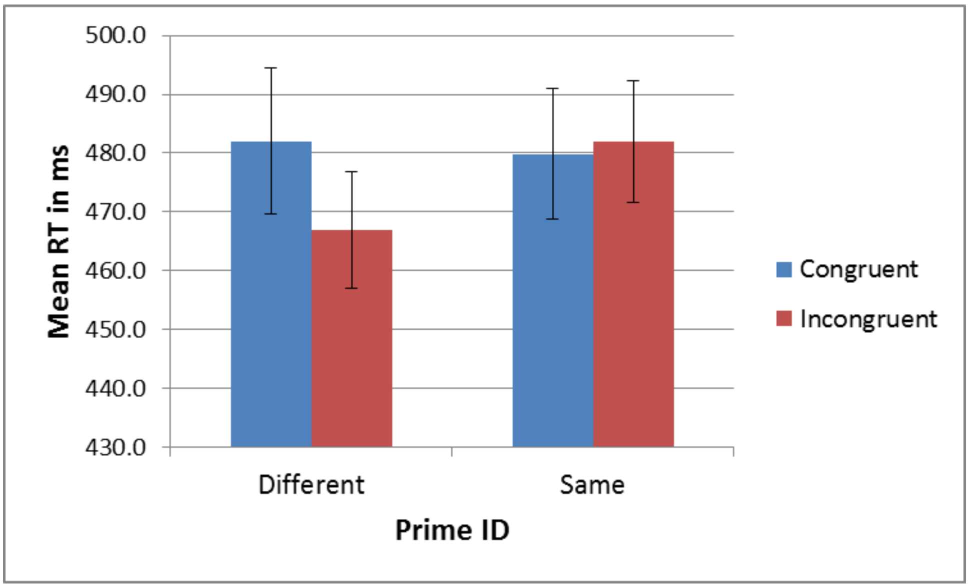

Figure 3b: Mean RTs as a function of Prime ID and Congruency collapsed across the short and long SOA conditions for the Fast group in Experiment 3.

With regard to the fast group, a close inspection of the data indicated that the prime ID by congruency effect was caused largely by a reduction in RTs in the incongruent trials when the prime ID was different (see Figure 3b). In other words, whereas there was no evidence of WM guidance on attention in the prime ID same condition, the participants showed evidence for a reversed WM effect in the prime ID different condition. One way to interpret this pattern of data is to assume that although the stimuli in the same category as the items in the memory set did not appear in the memory set, they were nevertheless activated to some extent. In the prime ID same trials, a memory set stimulus re-appeared as a prime. As in the case with the slow participants, the much stronger activation associated with this stimulus relative to the stimulus in the other category could make disengaging attention from the critical prime more difficult, both when the target appeared near the location of the critical prime or at the location of the other prime. In contrast, in the prime ID different condition, the stimuli in the same category as the items in the memory set were only weakly activated. This could make the disengagement of attention easier, especially when the target appeared at the location opposite to the location of the critical prime item. Related results have been reported by Houtkamp and Roelfsema (2006) and Moores et al. (2003). In both studies, evidence for WM guidance of attention was found when a search target was absent, but not when it was present. I will return to this topic in the general discussion section.

General Discussion

The main focus of this thesis is to investigate whether the guidance of visual attention from WM can be generalized from a specific stimulus or a task to a category. To briefly recap, prior neurophysiological and behavioural studies have suggested that attention can be guided by the contents of WM (e.g., LaBar, Gitelman, Parrish, & Mesulam, 1999; Downing, 2000; Huang & Pashler, 2007; Olivers et al., 2006). Furthermore, WM contents can capture attention involuntarily even when they are detrimental to the task at hand (e.g., Soto et al., 2005; Soto et al., 2006a). In most previous studies, the guidance of visual attention by the contents of WM is confined to specific stimuli (e.g., Downing & Dodds, 2004; Soto et al., 2005; Olivers et al., 2006). For example, performance was enhanced when there was a match between a stimulus in a search display and the contents held in WM (e.g., Soto et al., 2006a, b; Soto & Humphreys, 2006). However, it is possible that this effect can go beyond specific stimuli and occur at a more abstract level such as the level of category. The overall goal of this thesis was to investigate this possibility.

Experiment 1 tested whether maintaining a set of stimuli of a specific category in WM would influence participants' deployment of visual attention to favour other stimuli that belonged to the same category. Experiment 2 further manipulated the SOA between the prime and target display to determine whether the results of Experiment 1 were associated with the lack of time for attention to be focused onto the critical prime for WM guidance to exert its influence. In both experiments, the stimuli held in WM never appeared in the prime display. The final experiment was designed to discourage participants from adopting the strategy of inhibiting all the stimuli not present in the memory set. Taken together, the most important results of the experiments reported in this thesis can be summarized as follows:

1. When the stimuli held in WM never reappeared in the prime display in Experiments 1 and 2, there was no evidence that maintaining specific stimuli in MW biased the distribution of attention to other stimuli within the same category.
2. When the stimuli held in WM could reappear in the prime display on some

trials in Experiment 3, the participants whose RTs were relatively slow showed a non-spatially specific cost in both RTs and accuracy when the critical prime was one of the WM items relative to new items from the same category.

3. Contrary to those in the slow group, the participants in the fast group in Experiment 3 showed evidence for WM guidance of attention in the prime ID different condition. RT was slower when the target appeared at the location near rather than far away from the stimulus in the same category as the stimuli held in WM, suggesting category-based WM guidance of attention. No congruency effect was found in the prime ID same condition.

WITHIN-CATEGORY WM GUIDANCE OF ATTENTION

Experiments 1 and 2 in the present study found no evidence that maintaining a set of stimuli in WM biased the distribution of spatial attention to the location of the other stimuli within the same category. In other words, there was no indication, at least in these experiments where the stimuli held in WM never appeared as a prime in the search display, that the stimulus-specific or task-specific WM effects observed in previous studies could be generalized to the level of category.

Several factors might have contributed to the present results. The first factor relates to limited attentional resources. WM driven attentional guidance may depend on having enough spare resources (Downing & Dodds, 2004; Lavie, Hirst, de Fockert, & Viding, 2004; Lavie & de Fockert, 2005). Several studies have shown that an increase in WM load could reduce or abolish the effect of WM on attention (e.g., Houtkamp &

Roelfsema, 2006; Soto & Humphreys, 2008 Experiment 4). As WM load increases, fewer resources are available to support efficient target selection and/or distractor rejection resulting in no observable effects of WM guidance of attention (see Soto, Hodsoll, Rotshtein and Humphreys, 2008, for a review).

In the present study, the participants were required to memorize four different letters or numbers in every single trial while performing the shape discrimination task. In most previous studies that showed WM guidance on attention, participants were typically required to hold only one item in mind (e.g., Olivers et al., 2006; Soto et al., 2005). The high WM load in the current experiments might have depleted the participants' attentional resources and increased the difficulty of the subsequent shape discrimination task. In order to better perform the target discrimination task, any strategies that could be used to prevent interference from the contents in WM might be helpful; and the easiest way to block such interference would be to inhibit all the information not immediately useful on a given trial (i.e., the same-category stimuli not presented in the memory set and the stimuli in the other category). Such a strategy would lead to the null results found in Experiments 1 and 2.

The second factor that could give rise to the absence of the WM effect is the close relationship between numbers and letters. Alphanumeric characters are frequently used together in everyday life (e.g., license plate numbers, computer password, etc.). In the present study, all the numbers and letters were equally relevant to the on-going task as any letter or number could be a potential memory item. Because of this, both categories could be highly activated in WM, and they could have comparable influence on the allocation of attention regardless of the actual memory items on a given trial. With both number and letter presented within the same prime display, any WM effect might be obscured.

The third factor concerns the question whether different types of WM have differential effects on the guidance of visual attention allocation. WM has been traditionally said to comprise separate subsystems for verbal and visual information that selectively interfere with verbal and visual tasks, respectively (see, e.g., Baddeley, 1996, 2003; Jonides, Lewis, Nee, Lustig, Berman & Moore, 2008; Logie, 1990; Repovs & Baddeley, 2006). It is conceivable that under some situations only visual working memory interferes with visual attention. Consistent with this, Olivers et al. (2006) found that a distractor matching the remembered colour only interfered with visual search when the colour was very difficult to encode verbally (e.g., observers were given different shades of yellow), but not when it was easy to encode (e.g., red vs. yellow). Olivers et al. (2006) proposed that the difficulty in verbalization forced their observers to adopt a more visual memory representation in the former case, resulting in WM guidance of attention. In the present experiments, the memory items were easily distinguishable and their verbal labels were also readily available (e.g., "eight" as the verbal label for "8"). The participants might choose to use verbal coding, and this in turn could result in the null results observed in Experiments 1 and 2 of the present study. However, it should be noted that there are also other studies that used easily verbalized WM stimuli, and the researchers still found WM effects (e.g., Soto et al., 2005; Soto &

Humphreys, 2007). Further investigations are needed to understand these seemingly inconsistent results.

NON-LOCATION SPECIFIC ATTENTIONAL CAPTURE

The major difference between Experiment 3 and the previous two experiments is the inclusion of a WM item on some trials in the prime display. When the data were split into two groups based on the participants' RTs, the slow group showed slower RT when the prime item was one of the WM items. Two things are worth noting here. Firstly, there was interference from the WM content on target discrimination that led to slower responses, and this interference was independent of the location of the WM matching item. Secondly, items that belonged to the same category as the WM items did not have the same effect on attention (if any) as the WM items.

As mentioned previously, Moores et al (2003) reported similar results in their experiment. They found that RTs to a probe were independent of the location of the probe relative to the search target or an object associated with the target. Furthermore, in their experiment, RTs were significantly faster in the target-absent condition than in the target-present condition. Based on these and other related results, they concluded that both the target and target related objects generated a "highly reliable general cost" (Moores et al., 2003, p. 184) which impaired performance. They also suggested that the slower RT in the target-present condition indicated that the target captured attentional resources, delaying the responses to the probe. In the present study, the slower RT on the gap discrimination task occurred regardless of the location of the WM-matching items. This could also indicate that the WM-matching prime generated a general cost and captured attentional resources, making responses to the probe slower than when a WM-matching prime was absent.

Furthermore, the main effect of Prime ID for slow group indicates that new stimuli, even though they belonged to the same category as the WM items, did not have the same effect on the allocation of attention as the WM-matching primes. One way of explaining this result, as mentioned previously, is that a WM-matching prime was activated more strongly than a stimulus not held in WM. This stronger activation could make attention more difficult to disengage, resulting in longer RTs to the target in the subsequent display in the prime-ID same than prime-ID different condition. It also could be that the content in WM might have interfered with prime processing and/or target discrimination, but the extent of interference might be depended on the similarity between the WM item and the prime item. The more similar they were, the more stronger interference an item held in WM would have on prime processing and/or target discrimination. Apparently, when the prime was identical to the WM item, it reached the maximum similarity which could result in the biggest interference. Another possibility is that since the primes in the prime ID different condition did not enter WM in the first place, they could not be "deleted" from WM as they did not exist in WM. Therefore, there is no real-time cost associated with them relative to primes in the prime ID same condition. Different primes never appear as memory probes so there is no gain from processing them past the point of classification as "not-to-be-remembered". If the prime processing or target discrimination could be modulated by the identity of the prime, then the prime item must have captured attention. That is, although the slower

RT found in prime ID same trials does not necessarily reflect a shift in visual attention to the location of the WM matching item, attention must be captured by a WM-matching prime in a non-location specific way in order to perceive the identification of the prime items.

DELAYED DISENGAGEMENT OF ATTENTION

For the fast responding group, the RTs were longer when the target appeared at the location below the critical prime (482ms) compared to when it appeared at the opposite location (467ms) in the prime ID different trials. No such effect was found in the prime ID same condition. Compare with the stimuli from the other category, WMC-matching prime seemed to evoke a reverse attentional effect in the prime-ID different condition. This pattern of data suggested that the difficulty of disengaging attention from the critical prime might depend on the strength of the relationship between the prime items and the WM-items. Similar to my previous discussion, when the prime item was identical to the WM-items, the strength of the relationship between them was the strongest. It was so strong so that no matter where the upcoming target would appear, it would be equally difficult to disengage attention from the WM-matching critical primes. When the prime items were only related to the WM items, they were relatively more activated than the stimuli in the other category due to spreading activation (see Collins & Loftus, 1975, for a review) but they were less activated than the WM-matching items. The relationship between the critical primes and the WM items was just strong enough to engage attention and was just weak enough to disengage attention. That is, it wouldn’t be as difficult as for WM-matching items when disengaging attention from itself. Consequently, if there was any effect from the contents in WM, it might be more pronounced in the prime ID different condition. The pattern of data in the present study coincided with this proposal. So far, the current discussion is more inclined to suggest that WM-matching and WMC-matching stimuli might both draw attention; but, they might differ in how difficult the attention could be disengaged from them.

INDIVIDUAL DIFFERENCES IN THE EFFECT OF CATEGORY-BASED WM GUIDANCE OF ATTENTION

The contents of WM appeared to influence the two groups of participants in different ways. Whereas the participants who were relatively slow (i.e., the slow group) were influenced by specific items held in WM in a more general way in that the re-appearance of these items delayed RTs to the search target, there was no evidence that the stimuli held in WM guided attention to a specific location in the display. For the fast group, the effect of the contents of WM was more complex. The participants showed evidence of category-based WM guidance of attention when the critical prime was a stimulus in the same category as the stimuli held in WM, but not a stimulus actually held in the WM. This could be due to the different levels of activation of the stimuli associated with the items held in WM, with the activation level higher for the participants in the fast group than in the slow group.

The participants in the fast and slow groups might also differ in working memory capacity (or span), with the fast group having a relatively bigger working memory capacity than the slow group. Working memory capacity is a critical cognitive characteristic that has a major impact on the quality of cognitive performance. Many researchers have suggested that individual differences in WM capacity is associated with the level of attentional control over the use of WM resources (Bleckley, Durso, Crutchfield, Engle, & Khanna, 2003; Kane, Bleckley, Conway, & Engle, 2001; McNab & Klingberg, 2008; Vogel, McCollough, & Machizawa, 2005). A fundamental aspect of the attentional control is the ability to inhibit distracting information (Dempster, 1991). Several studies have shown that people who have a larger working memory capacity (i.e., high-span participants) are better at inhibiting distracting information than those who have a relatively small working memory capacity (i.e., low-span participants) (Conway & Engle, 1994; Conway, Tuholski, Shisler & Engle, 1999; Gernsbacher, 1993; Hasher & Zacks, 1988; Rosen & Engle, 1997). For example, Vogel et al. (2005) provided evidence that high-span individuals are much more efficient at excluding distractors from consuming memory capacity than low-span individuals are. To measure selection efficiency, the researchers (Vogel, Woodman and Luck, 2001) recorded the event-related potentials that reflected the encoding and maintenance of the items held in WM. In their experiments, the participants performed a visual memory task that required them to remember selectively only a few relevant items from within an array. The results showed that under many circumstances the high-span individuals were more efficient at encoding and representing the relevant information in WM relative to the low-span individuals, who appeared to be less able to filter out irrelevant information and to prevent them from consuming WM resources.

Research using brain-imaging techniques has also shown that the ability to inhibiting irrelevant information is related to individual differences in working memory capacity (Mecklinger, Weber, Gunter & Engle, 2003). Meclinger et al. (2003) found enhanced prefrontal cortex activation in individuals with high working memory capacity when performing a letter recognition task. Because the prefrontal cortex plays a crucial role for actively maintaining the relevant information in working memory, Meclinger et al. (2003) suggested that these high capacity individuals were able to allocate more attentional resources for the maintenance of task goals in the face of interfering information. If WM capacity indeed played a role in the present study, how it interacted with the prime ID remains unclear. Further experiments are needed to investigate this issue.

Furthermore, it is noted that in the present experiments, the prime display consist both number and letter. It has potential drawbacks. Because both categories were relevant in the current experiments, all the primes used in the experiments could be considered as task relevant. As the experiment proceeded, both the number and letter categories were more or less activated to the same degree. When they appeared on the display simultaneously, it could be difficult for the WM-matching item to reveal its effect on the allocation of visual attention. Therefore, it would make sense to include condition(s) such that only one related prime (e.g., N + ＊) or none of the related primes (e.g., ＊ + #) were included. The former should be able to avoid the possible interference and/or competition from the activated other category primes and give a clearer picture of the effect from the content in WM on attention, and the later could provide a baseline against which the guidance of attention from WM could be measured. It should therefore enable us to differentiate whether the content in WM could facilitate or hinder the allocation of attention. Including such conditions in further experiments will be beneficial.

Conclusion

Overall, the current study did not find evidence that the guidance of visual attention from WM could be generalized from a specific stimulus or a task to a category under all conditions. However, the results showed that WMC-matching stimuli produced a location independent cost on an immediately following but unrelated gap discrimination task in those participants whose reaction times were relatively slow. In contrast, the participants whose reaction times were relatively fast showed evidence of category-based WM guidance of attention. The pattern of findings thus indicates that how the contents in WM could affect visual attention depends on multiple factors. The underlying relationship between what is maintained in WM and how it affects visual attention is more complex than biased competition theory and related theories of attention can accommodate. Although the present study failed to find evidence that attention can be automatically drawn to items associated with the contents of working memory under all situations, there is evidence that WM contents and/or items related to the stimuli held in WM could affect the distribution of attention under certain conditions in some participants as described above. These results, together with the findings of previous research, provide additional evidence for a close link between WM contents and attention distribution.

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