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# WORKING MEMORY CONTENTS AND THE TIME COURSE OF INFLUENCE ON VISUAL ATTENTION

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# WORKING MEMORY CONTENTS AND THE TIME COURSE OF INFLUENCE ON VISUAL ATTENTION

A DISSERTATION APPROVED FOR THE
DEPARTMENT OF PSYCHOLOGY

BY

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# DEDICATION

To

my parents, Heinz and Ursula Lorat,

and Carolina Berdugo.

# ACKNOWLEDGEMENTS

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# ABSTRACT

Working memory and attention are closely related concepts. Capture of visual attention by working memory (WM) contents has generated much interest in recent years. However, there is a lack of literature related to the time course of this attentional bias. In this dissertation I argue for a differential time course of WM driven attentional capture, for basic features and semantically related LTM contents, based on differences in activational pathways. Three experiments were designed to test these assumptions. Participants memorized a prime, for a later memory task. After a variable stimulus onset asynchrony (SOA), they then saw a search display for a target decision task. One of the items in the search display could contain a distractor item, related or unrelated to the WM content. In Experiment 1 primes and distractors consisted of basic features, colors and shapes. Experiment 2 investigated semantic and color primes in a single paradigm, using country names, with associated capitals and flags. Experiment 3 investigated primes semantically related to stylized objects. In support of the hypotheses, I found evidence that basic features held in WM attract visual attention rapidly, at very short intervals, while stimuli semantically related to WM contents develop attentional bias only at longer intervals. Additionally I found support for an inhibitory mechanism, leading to attentional allocation *away* from task irrelevant distractors associated with WM contents. The results support the differential time course of attentional effects of WM contents, based on type of stimuli, and highlight the importance of time course analysis when studying these effects.

# CHAPTER I

# INTRODUCTION AND LITERATURE REVIEW

We are subjected to an immense amount of sensory information at any given moment in time. The fact that the human cognitive system is capacity limited and cannot process all information entering the sensory system has been thoroughly established (for example Broadbent, 1958; Treisman, 1969; Tsotsos, 1990). Therefore, one of the tasks of the human information processing system is to select relevant sensory information for current tasks and behavior, while at the same time filtering out irrelevant information. In many situations memory helps guide this selection mechanism. For example, if we search for our keys we have access to a mental representation of the keychain, or if we search for a friend in a crowded bar, we have access to information from memory about how the face of our friend looks like. In other situations the contents of working memory (WM) can help guide visual search. Say you are trying to find a fitting piece while solving a puzzle. You might focus on a tile that has a distinct color (e.g. a brown “door” tile) or line segment. You can then use this feature, held active in WM, to guide search for a matching similar tile, which shares the same features. For example any tile that is also predominantly brown in color draws attention and guides your visual search, facilitating detection. The mechanisms of how working memory contents influence visual attention have been of much debate in recent years.

In their influential biased competition model, Desimone and Duncan (Desimone, 1998; Desimone & Duncan, 1995) argue that the capacity limitation problem is resolved through competition for processing; that is, stimuli – e.g. in a visual scene – will compete for the limited attentional and perceptual resources. For example Lavie and colleagues (Lavie, 2005; Lavie & de Fockert, 2003; Lavie, Hirst, de Fockert, & Viding, 2004) have shown that an increase in perceptual load leads to a decrease in distractor processing, demonstrating that task relevant targets receive preferential resource allocation, in the light of limited available perceptual resources. This highlights an important aspect of the biased competition model of visual attention. Desimone and Duncan (1995) argue that the competition for resources can be influenced, both via bottom-up and top-down mechanisms (Beck & Kastner, 2009; see also Theeuwes, Atchley, & Kramer, 2000; van Zoest, Donk, & Theeuwes, 2004). Top-down influence is thought to originate from working memory, located in the prefrontal cortex (Ungerleider, Courtney, & Haxby, 1998), while bottom-up processes are stimulus driven, originating from the sensory cortex (Buschman & Miller, 2007).

In the following sections, I will briefly describe the close connection between perception, attention and memory in context of how features related to working memory contents guide attention, and argue how types of stimuli could differentially influence the time course of the interaction between working memory and attention, particularly how visual-perceptual stimuli and semantically associated stimuli influence the time course of working memory driven attentional capture.

## Neurophysiological Connections between Working Memory and Perception

There is a strong neurophysiological connection between WM and visual perception areas, providing a physiological basis for the association between working memory and attention. This connection also provides a foundation for the proposed differential time course effects of the working memory and attention interaction.

Visual processing in human visual cortex follows two major pathways (Mishkin, Ungerleider, & Macko, 1983; Ungerleider & Haxby, 1994). The dorsal pathway, from V1 to the parietal lobe, is mainly involved in “where” information, like spatial information and motion. The ventral pathway processes information about object features (such as color, shape, or pattern) and object identity, and spreads from the visual cortex to extra-striate, temporal areas (e.g. inferior temporal cortex, Tsunoda, Yamane, Nishizaki, & Tanifuji, 2001).

Objects are represented through activation in the inferior temporal cortex (IT). Activity in different IT locations reflects certain features of objects (Tsunoda, et al., 2001). Working memory contents can influence activity in those areas. For instance Fuster, Bauer and Jervey (1985) demonstrated that the prefrontal cortex, through feedback connections, is responsible for heightened activation in IT during delay tasks, in monkeys. They found limited delay activity in IT, when the prefrontal cortex is deactivated (cooled). It is likely that these findings generalize to humans, as the similarity between monkey and human visual working memory system has been reported (Ungerleider, et al., 1998). In humans, it has been shown that working memory can influence even the earliest perceptual areas. Munneke, Heslenfeld, and Theeuwes (2010) showed heightened activity in V1, V2, and V3 when a location was held active in WM during a spatial WM task.

Chelazzi, Miller, Duncan and Desimone (1993) found that cells, preferentially responsive for a certain stimulus, showed enhanced activation while the stimulus was held in WM. Utilizing single cell recording of neurons in monkey IT, they found that when monkeys had to hold a cue in working memory during a delayed match to sample task, cells that where maximally sensitive to the cue (referred to as “good” cue) showed heightened activation, compared to when a “poor” stimulus was the cue. Additionally, they found evidence for enhancement or suppression of neuronal activity, based on if the cue was the target or not. When two stimuli (one “good”, one “poor”) where presented simultaneously in the receptive field of the cell, activation was enhanced, when the “good” cue was the target, and suppressed when the “poor” cue was the target. Even though both were projected onto the same receptive field of the cell, they behaved as if only one stimulus was present, seemingly “narrowing” the receptive field, as if it only encompassed the relevant stimulus (see also Chelazzi, Duncan, Miller, & Desimone, 1998). Desimone and Duncan (1995) suggest that this neural response modification reflects the resolution of the biased competition. In addition, it was also found that working memory contents can “pre-activate” associated perceptual areas. Neurons sensitive to WM contents show heightened activity during delay periods, even without visual stimulation (Chelazzi, et al., 1998; Chelazzi, et al., 1993). This pre-activation is seen as an argument for how working memory contents can bias the competition for selection, by providing a “head start” to features of objects held in WM.

## Working Memory and Attention

The basis of why working memory contents should influence attention lies in the strong connection between those two concepts, and indeed, just like between WM and perception, many have also argued for the close relation between working memory and attention, and demonstrated functional as well as neurophysiological overlap (Awh & Jonides, 2001; Awh, Vogel, & Oh, 2006; Chun & Turk-Browne, 2007; LaBar, Gitelman, Parrish, & Mesulam, 1999; Mayer et al., 2007).

The importance of WM influence on attentional control has been suggested, for example, using the anti-saccade task (Engle, 2002; Kane, Bleckley, Conway, & Engle, 2001). Under increased WM load, participants showed decreased inhibitory control. Similarly, low WM span individuals made more errors and were slower in correcting these errors. The role of WM in the control of visual attention has further been demonstrated by de Fockert, Rees, Frith and Lavie (2001). When projecting famous names on top of congruent or incongruent famous faces, which were otherwise task irrelevant, incongruent faces showed larger interference effects under high WM load compared to low WM load. De Fockert et al. argued that the increase in distractor processing under high WM load indicates the essential role of working memory for attentional control and distractor inhibition. They supported this conclusion via functional MRI. Under high WM load visual cortex activation was elevated, as compared to low WM load, indicating increased distractor processing under high load conditions (see also Agam & Sekuler, 2007; Lavie & de Fockert, 2005). The importance of WM control for visual search has also been shown. Visual search efficiency is impaired under high WM load, compared to low WM load (Han & Kim, 2004; Woodman & Luck, 2004; however, see also Woodman, Vogel, & Luck, 2001). These findings highlight the important role working memory holds in relation to attentional allocation. This role becomes further evident when considering attentional capture of working memory contents.

## Working Memory Contents and Attentional Capture

As mentioned above, Desimone and Duncan (1995) argue for a top-down bias in the competition for selection. Features of objects held in WM are thought to be pre-activated, and receive an advantage in the competition for selection. This led to the prediction that contents of working memory will attract attention automatically.

Awh, Jonides, and Reuter-Lorenz (1998), for instance, showed that spatial WM contents can influence attentional allocation. In their study, participants showed better performance in a shape discrimination task, if the target fell at the memorized location compared to a non-memorized location. Similarly, Downing (2000) observed that a face stimulus held in WM attracts attention on a subsequent probe detection task. Huang and Pashler (2007) found an increase in reporting frequency for numbers projected on geometric objects held in WM, compared to the numbers projected on novel objects. Mere repetition of a stimulus, without the necessity for holding the stimulus in WM, does not influence attentional selection (Downing, 2000; Lorat, 2008; Olivers, Meijer, & Theeuwes, 2006; Soto, Heinke, Humphreys, & Blanco, 2005), indicating that it is indeed the WM content that drives attention, not just bottom-up priming (Moores & Maxwell, 2008).

In addition, it seems that this capture is automatic and does (at least initially) not underlie executive control (but see Downing & Dodds, 2004; Woodman & Luck, 2007). For instance, features held in WM interfere with tasks that require those features to be inhibited. For example, when color information is held in WM, it interferes in a subsequent shape discrimination task, where attention to color is detrimental to task performance (Lucas & Lauwereyns, 2007). Soto et al. (2005) used a dual task paradigm, where they first showed participants a geometric shape of a certain color, which had to be held in memory, three times in rapid succession. This was followed by a display containing objects of different shapes and color. The task was to determine the direction of a tilted line displayed within the target shape. RT was slowed when the memory prime was used as a distractor in the line-tilt task, compared to WM content unrelated distractors. In addition they showed that this effect was mainly driven by color. When the prime shape reappeared in the search display, the overlap in shape by itself had little effect. However, there was a slightly stronger effect when both color and shape matched the memory item. They used a relatively short cue presentation time (three times 35ms cue presentation with a 12ms blank screen in between each) and a short stimulus onset asynchrony (SOA, 188ms). It is possible that shape information takes longer to be activated than color. Therefore, with longer SOA or longer presentation time, the overlap of shape between the prime display and the search display could have influenced subsequent visual search performance. Indeed, Olivers, et al. (2006, Experiment 4) showed WM content related capture for both color and shape when using longer SOA. They too had participants memorize a shape/color combination, displayed for 150ms.

Participants were instructed to either memorize the color, or the shape. This was followed by a 4000ms blank screen and a letter discrimination task, where one of the items on the screen could act as a distractor, overlapping in none, one, or both features with the memory item. They found feature specific attentional capture. RT was slowed only when the memorized feature was present as a distractor in the letter discrimination task. For example, color only interfered when it was the critical feature, and did not interfere when participants had to memorize shape only and vice versa.

However, it is important to note that some studies failed to find WM content related capture. Neither Downing and Dodds (2004), nor Woodman and Luck (2007) found evidence that WM contents draw attention automatically. In fact, they found indication that participants could strategically allocate attention, resulting in slightly faster RTs for trials, which contained WM contents as distractors (but see Olivers, 2009 for explanations).

Taken together these findings indicate that basic features of WM contents, at least color, can influence visual attention rapidly, at very short SOAs. This influence is largely involuntary and occurs even when detrimental to performance on subsequent tasks. However, the time course of influence on attention seems to be dependent on the type of stimulus. Capture based for example on shape of the WM content did not occur with short SOA (188ms, Soto, et al., 2005), but was observed with very long SOA (4000ms, Olivers, et al., 2006).

## Long-term Memory and Attentional Capture

Capture of visual attention has not only been found for features of objects currently held active in WM, but also for semantically associated concepts stored in long-term memory (LTM). Duncan and Humphreys (1989) suggest that the maintenance of the target template in working memory activates its representation in LTM. This activation can then spread to semantically related templates, which in turn can provide top-down bias in the competition for selection (Moores, Laiti, & Chelazzi, 2003). The associative nature of LTM contents has long been recognized (e.g. Anderson, 1983; Collins & Loftus, 1975). For example, color perception activates representation of color words and vice versa (Richter & Zwaan, 2009). Representations in LTM are connected with varying strength, which can be influenced by factors such as episodic and semantic relationship, or pictorial similarity (Estes, 1994, as cited in Moores, et al., 2003). Repeated, concurrent activation is thought to strengthen these connections (cf. long-term potentiation; Malinow, Mainen, & Hayashi, 2000; Teyler & DiScenna, 1987).

Just like working memory, long-term memory can influence visual attention. For example objects are detected faster if they are congruent with schemata (Biederman, Glass, & Stacy, 1973), and objects in LTM can influence guidance of attention, as well as dwell time (Chanon & Hopfinger, 2008). Associative memory has also been shown to affect visual attention in connection with working memory contents. For instance, Moores et al. (2003) found that objects associated with working memory contents influence visual attention; they are recognized more accurately and recalled more often than unrelated objects. In addition they found that these objects are more often the target of initial saccades, compared to unrelated distractors. Huang and Pashler (2007) also demonstrated attentional capture for associated memory. They found that, just like for geometric objects, numbers projected on words associated with WM contents were reported with higher frequency than chance. When memorizing “atom” for example, the number projected on “molecule” was reported more frequently than numbers projected on unrelated words. That semantic primes can automatically draw attention to associated objects was also observed (Soto & Humphreys, 2007). They used a similar paradigm as Soto et al. (2005). The prime in this case however, could either be a color/shape combination or a verbal prime (e.g. “Red Square”). Using a relatively long cue presentation time of 2000ms, they observed attentional capture effects for both types of primes.

Contrary to attentional capture of basic features, literature about capture of attention by associative memory contents is comparatively scarce. In addition, most studies that report attentional capture of associative memory, have used very long cue presentation times and/or SOA, in the order of seconds, compared to studies finding capture effects for basic features (e.g. 129ms cue, 188ms SOA;  Soto, Humphreys, & Heinke, 2006).

A major aim of the present study is to provide a formal comparison of the differential time course of WM content influence on visual attention, for basic perceptual features, like colors and shapes, and associative memory items, connected to WM contents.

## Time Course of Attentional Capture by Working Memory Contents

While the effects of WM contents on visual attention, both direct and for associative memory, and the close connection between working memory and attention have been of much research interest, the time course of how WM contents influence visual attention has generated only little literature; especially in terms of how this influence might temporally differ for associative memory.

Soto, Wriglesworth, Bahrami-Balani, and Humphreys (2010) found that contents of working memory can alter early stages of perceptual processing. They used a signal detection paradigm, and found that targets presented within WM associated context were detected with higher sensitivity than when presented within an unrelated distractor. Given that basic features are processed “early” in visual perception, this suggests that increased sensitivity benefits these features more, in terms of processing speed and therefore attentional allocation bias, than for associative memory contents, or more complex, “late” features/stimuli.

Huang and Pashler (2007) found an increase in reporting rate of numbers projected on WM contents with increasing SOA for geometric objects. However, here they only used SOAs of 0ms and 800ms. For associative WM content they found an increase between 400ms and 800ms, with no further increase with longer SOA. However, they did not look at shorter SOAs for this version. In addition, especially when using geometric objects, participants could have used the choice display as a memory aid, given that the objects were complex and confusable. Also, they did not analyze RT, but rather only measured reporting rate.

Soto and Humphreys (2008) investigated if the longer SOA used by Woodman and Luck (2007) – 500ms – or Downing and Dodds (2004) – 1500 and 2000ms – contributed to the absence of WM content related capture in those studies. They used a similar paradigm as Soto et al. (2005), but varied SOA (188, 504, or 1008ms). They found capture of the memory prime, independent of SOA. It is unclear however, if this capture was driven mainly by color, like in their previous study, or shape as well (Soto, et al., 2005). It could be that the shape feature shows initially small effect, as suggested by the lack of capture by shape alone in Soto et al. (2005), but develops capture effects with increasing SOA (see Olivers, et al., 2006). Soto and colleagues (Soto, et al., 2005; Soto & Humphreys, 2008; Soto, et al., 2006) also looked at the fastest RTs, and found that, for color, attentional capture in their studies occurred "early" after array onset. In addition, saccadic eye movement measures revealed the early processing of attentional capture by perceptual features (Soto, et al., 2005). In this study, first saccades landed significantly more often on an object matching the WM item in color, or both color and shape, but not shape alone. Olivers et al. (2006) found that initial saccades showed a small, but significant, latency advantage for WM content related distractors compared to unrelated distractors, consistent with increased sensitivity for WM content related features (Soto, et al., 2010). In addition, Olivers et al. also observed a higher proportion of first saccades towards WM content related distractors compared to unrelated distractors.

Dombrowe, Olivers and Donk (2010) looked at the time course of attentional capture in greater detail, using only visual primes, however, not associative memory, or verbal primes. They investigated three different cue presentation/SOA conditions (150ms/150ms, 500ms/500ms, 1000ms/2500ms), based on the timings used by Soto et al. (2005), Woodman and Luck (2007), and Olivers et al. (2006), respectively. Their paradigm was the same as in Olivers et al. (2006). When using easy to verbalize colors, they found initially strong effects of WM content related capture, which decreased for medium cue/SOA times, and disappeared at long intervals. Note, that the ability to verbalize the memory prime is not a required condition to find capture of WM contents (Olivers, 2009). The disappearance of the capture effect at long cue/SOA times could be an indication that sufficient time has passed to allow for strategic allocation of attention. Oberauer (2002) found that it takes about two seconds to organize memory material, so that passive, for the current task uninvolved, information does not interfere with a current task. This could also account for the lack of attentional capture effects under long cue/SOA timings in Downing and Dodds (2004).

When using “difficult” colors (i.e. exact variations of a color, difficult to differentiate) Dombrowe et al. (2010) found an opposite pattern; absence of WM capture at the short cue/SOA, with an increase in WM capture effects over time. This task is very difficult and cognitively demanding, as can be seen at the high error rate for the memory task (46% - 51%), and needs extensive cognitive control to maintain the target (see also Lorat, 2008). Dombrowe et al. suggest that this task may require a different strategy and therefore take longer to initiate. It is possible that initially more resources are devoted to encoding of the memory item, and only with increasing time sufficient time the WM representation is strong enough to provide the observed top-down effects on visual attention. It has been shown that the more complex visual information is, the longer it takes to consolidate into WM (Vogel, Woodman, & Luck, 2006). However, the difficulty of the task itself, in connection with the increased executive control demands, acts as a confounding factor that introduces other, unrelated mechanisms (see also Han & Kim, 2004; Woodman & Luck, 2004) that may account for the findings.

Soto and Humphreys (2007) used two different SOA conditions in their investigation of attentional capture of verbal WM contents. They either presented the prime for 2000ms or, in a different condition, until the participant had read the prime aloud. The experimenter then advanced to the next screen via key press. Although, they did not report how long participants took to read the prime aloud, it should have taken significantly less than two seconds to read “Red Square” out aloud. Their findings indicate that the capture effect was stronger in the 2000ms condition. In fact, it looks like the effect disappeared for color alone in the “read aloud” condition. However, they did not report statistics for this comparison. Conjunction match (both color and shape) on the other hand seemed to still induce WM content related capture.

In conclusion, while some research has been conducted to investigate time course effects for basic features, only anecdotal findings are available for associative or more complex information. No formal comparison of both types of stimuli is available at present.

## Rational for the present Experiments

The time course of WM content influence on visual attention has received comparatively little attention in recent literatures. This is true even more so for associative memory. Basic features of objects in visual working memory, especially color, show influence of attentional allocation early (Soto, et al., 2005). Working memory seems to utilize areas usually associated with perception, keeps those areas, which were previously activated during perception, more active during delay (Chelazzi, et al., 1998; Chelazzi, et al., 1993) and increases sensitivity to associated features (Soto, et al., 2010). According to the biased competition model (Desimone & Duncan, 1995) both bottom-up and top-down influences can bias the competition for processing. It is possible that in case of basic features and short SOAs both elements interact. Bottom-up effects are prevalent very early, but decay rapidly (e.g. less than 150ms, Theeuwes, et al., 2000), while top-down effects should increase over time. It has been shown that feedback networks from locations associated with working memory (PFC) first activate “later” processing stages in IT, moving backwards to “earlier” stages, like V2, and V1 (Buffalo, Fries, Landman, Liang, & Desimone, 2010; see also Naya, Yoshida, & Miyashita, 2001).

Rapid attentional capture effects by basic features was demonstrated for example by Soto and colleagues (e.g. Soto, et al., 2005; Soto, et al., 2006), who used relatively short cue and SOA times (see also Dombrowe, et al., 2010). It is possible that with long SOA times executive control is sufficiently available to inhibit involuntary WM capture effects (e.g. Dombrowe, et al., 2010; Downing & Dodds, 2004; Olivers, et al., 2006), as suggested by Oberauer (2002). In addition it seems that more complex features, like shapes, take longer to influence attentional capture (Olivers, et al., 2006), possibly because they take longer to consolidate into WM (Vogel, et al., 2006).

For associative memory we should see a different time course. Initially there should be little effect. The overlap between areas involved in prime perception and associative memory should be relatively small. Based on the spreading activation architecture of memory, we can assume that some time is spent to activate associated memory contents.

Then this activation needs to feedback into associated perceptual areas to “pre-activate” associated cells, which in turn influence the competition for selection for processing (Desimone & Duncan, 1995). Even though to my knowledge nobody has looked at the time course of associative memory to date, studies that found attentional capture have used relatively long cue and SOA times (Moores, et al., 2003; Soto & Humphreys, 2007). Therefore I expect no attentional capture of WM content associated memory at very early SOAs. However, this effect should increase over time. It might be possible to see a similar decrease again at very long SOAs, as is expected for basic features of visual WM contents.

# CHAPTER II

## EXPERIMENT 1A & 1B

In this set of experiments I compare the time course of how working memory contents influence visual attention. More specifically this first set of experiments compares verbal and visual cues, as well as differences between basic feature types, namely color and shape.

Visual cues should directly pre-activate associated visual areas, while this pre-activation is reinforced through feedback activation from working memory (PFC). Theeuwes et al. (2000) showed that – for salient distractors – bottom up effects on visual attention were initially strong, but decayed rapidly, while top-down effects increased over time. I propose a similar mechanism for attentional capture of working memory contents. Notice however, that bottom-up priming alone does not seem to be sufficient to explain observed capture effects. For instance, Soto et al. (2005, Experiment 3) flashed a prime three times in rapid succession, followed by a 188ms blank period and found attentional capture of the prime only when it had to be held in working memory. When the same procedure was used without the requirement to hold the prime in WM they found no effects on visual attention. Bottom-up activity effects are rapidly decaying, unless re-activated, or maintained, via top-down feedback. Theeuwes et al. (2000), found bottom-up effects only at SOAs of 50ms and 100ms, but not at 150ms or more. The longer SOA used by Soto et al. (2005) could have been long enough for any bottom-up priming effects to have decayed, therefore not showing an influence on visual attention. The maintenance of activity in perceptual areas through feedback from WM is a necessary precondition to see later effects of WM content related distractors on attention. I hypothesize that WM influence is observed more rapidly however, if activity in perceptual areas needs to be kept from decaying, instead of having to be completely (pre-) activated from baseline. The idea that both, bottom-up and top-down effects may interact to influence attentional capture was supported by Soto, Humphreys and Heinke (2006). They found evidence of attentional capture of WM contents even in the context of highly salient objects. Features of WM contents slowed response time for salient targets when acting as a distractor, and even increased RT when the salient target was the WM content. In addition I propose that attentional capture is found earlier for more basic features, like color, compared to more complex basic features, like shape. Indication that color guides attention more than shape was provided by Williams (1966), who found faster performance for objects defined by color, than shape in a search task. In addition he found that objects defined by color were the target of initial saccades more frequently.

Buffalo et al. (2010) found that top-down effects on attention are first evident in later areas of the ventral stream, like inferior temporal cortex (IT), responsible for object identity, moving in a feedback fashion towards earlier stages (e.g. V2, V1). This suggests the same mechanism may be responsible for more complex stimuli. For abstract, non-visual stimuli, semantic information may be activated before activation spreads to earlier processing stages. For verbal cues no visual representation of the distractor is originally activated. Only after the semantic meaning has been processed, mechanisms of spreading activation should, via feedback from PFC, pre-activate visual areas associated with the prime. I propose that this takes longer, given a more complex feedback path, than maintaining activity, or keeping activity in previously activated areas from decaying completely.

Therefore, providing a visual cue to be held in WM, perceptually similar to the distractor, should show capture of WM contents at shorter SOAs than when providing a semantically related verbal cue. To test this prediction participants are either cued visually or verbally (e.g. a picture of a triangle or the word “triangle”; see also Soto & Humphreys, 2007). After an SOA of varying length they then see a display of eight objects for a letter discrimination task, where a different exemplar of the memory prime can appear as a distractor. Visual attention capture effects of features related to WM content should be observed faster for visual cues, than verbal cues. Similar to the findings of Dombrowe et al. (2010), it is possible that, especially for the visual cues, the effect of WM contents on visual attention will decrease at very long SOAs, due to inhibitory control mechanisms (Oberauer, 2002). Experiment 1a will investigate effects of shape, while Experiment 1b will look at color features. Given previous findings that shape features only showed attentional capture effects at longer SOA (Olivers, et al., 2006) but not very short SOA (Soto, et al., 2005),  I expect to find that visually cued colors will show effects at earlier SOA than visually cued shapes. For both types of features I expect that verbal cues develop attentional capture effects at later SOAs than visual cues.

## Methods

### Participants

Based on estimated power, assuming small effect size, (G*Power 3; Faul, Erdfelder, Lang, & Buchner, 2007) and literature review, 15 participants each were recruited for Exp. 1a (4 male), age 18 – 25 (*M* = 20.56, *SD* = 2.19), and Exp. 1b (1 male), age 18 – 23 (*M* = 19.60, *SD* = 1.25), via the University of Oklahoma research participation system, for partial completion of course credit.

### Apparatus

Stimuli were presented on a 19” Dell monitor, controlled by a 3.4 GHz Pentium 4 Dell Optiplex GX 745 computer. Distance to the monitor was approximately 60cm. Stimulus presentation and data recording were controlled via E-Prime 2.0 (Psychology Software Tools, Pittsburgh, PA).

### Procedure and Stimuli

Experiment 1a and 1b used the exact same procedure. The only difference being the type of stimuli used. Participants first viewed a prime display for 500ms, displaying a visual WM prime (*visual* condition), a geometric object (triangle, oval, hexagon, or rectangle) in Experiment 1a, or a colored circle (red, green, blue, or yellow) for

Experiment 1b, or the respective word prime (*verbal* condition), displayed at the center of the screen in white color on a black background. This was followed by a blank screen, visible for a variable stimulus onset asynchrony (SOA; *100ms*, *300ms*, *600ms*, *1200ms,* or *2000ms*). Then a display of eight grey circles, arranged on an imaginary circle on the center of the screen, with equal distances, was shown. One of the circles acted as the target and contained either the letter “M” or “N” in white color. Participants had to indicate as fast and accurately as possible which letter was displayed, via key press, using the respective letters on the keyboard. One of the circles not containing the target could randomly act as a distractor, containing a different exemplar of one of the geometric objects (Experiment 1a; see Appendix A) or colors (e.g. different shade of red than the one used as a prime; Experiment 1b). Fifty percent of trials contained a distractor, and 1/3<sup>rd</sup> of distractor trials contained a working-memory related distractor. The stimulus

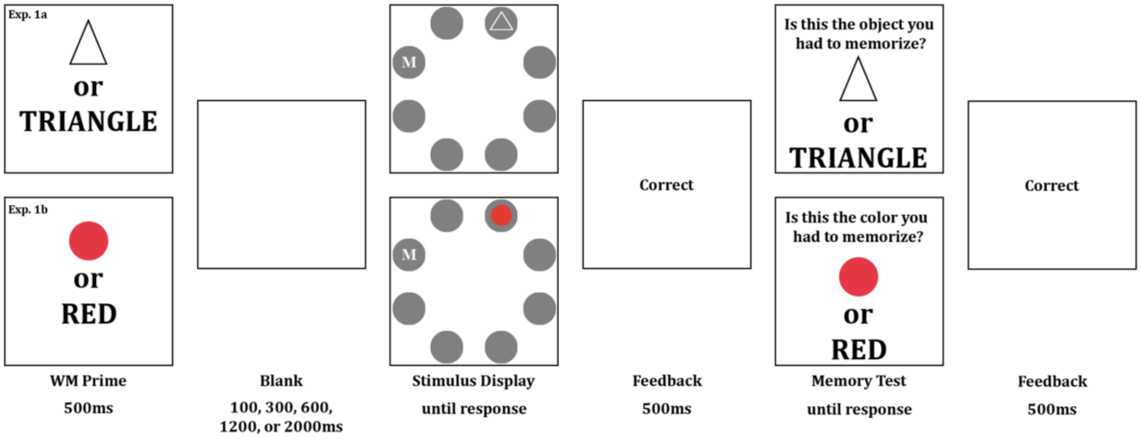


Figure 1. Example of the procedure in Experiment 1a (shapes) and 1b (colors), for both conditions (*visual* and *verbal*).

display stayed visible until response, followed by a 500ms feedback display. Then a memory test display was shown. One color, or color word (Exp. 1a), or geometric object, or object name (Exp. 1b), depending on condition, was visible at the center of the screen. The display contained the memory prime in half the trials and one of the other primes in the other half. Participants had to indicate if the correct memory prime was shown, via key press (“M” for same and “N” for different). This was followed by another 500ms feedback displays. The next trial was preceded by a 500ms blank screen. The first block was a practice block, consisting of 15 trials, followed by 4 blocks of 120 trials each, for a total of 480 trials.

## Results

Only trials with correct responses on both test (target identification and memory test) were analyzed. Data from three participants in Exp. 1a and one participant in Exp. 1b were excluded from data analysis. In Experiment 1a, one participant showed low accuracy for the memory test (less than 50%) and the other three participants (two in Exp. 1a) showed an extensive speed vs. accuracy trade-off with median RT more than three standard deviations above the mean. Accuracy was generally high, with a mean percentage of accurate trials for the target identification of 96.25% in Experiment 1a and 95.56% in Experiment 1b. For the WM test mean percentage of accurate trials was 93.62% in Experiment 1a and 91.83% in Experiment 1b (see Table 1).

In both, Experiment 1a (shapes) and 1b (colors), trials containing no distractor (Exp. 1a: *M* = 784.73, *SD* = 90.18; Exp. 1b: *M* = 801.18, *SD* = 71.66) were faster than trials

| | | Stimulus Display | | Memory Test | |
|---|---|---|---|---|---|
| | | Distractor Type | | | |
| Experiment | SOA | Related | Unrelated | Related | Unrelated |
| Exp. 1a | 100 ms | 97.40% | 94.27% | 94.27% | 91.67% |
| | 300 ms | 97.92% | 96.35% | 95.31% | 90.63% |
| | 600 ms | 95.83% | 95.31% | 93.23% | 95.05% |
| | 1200 ms | 96.35% | 95.83% | 96.88% | 91.41% |
| | 2000 ms | 97.40% | 95.83% | 94.79% | 92.97% |
| Exp. 1b | 100 ms | 93.75% | 96.43% | 92.41% | 91.52% |
| | 300 ms | 95.98% | 96.65% | 89.29% | 91.74% |
| | 600 ms | 94.20% | 95.98% | 95.09% | 89.73% |
| | 1200 ms | 94.64% | 97.10% | 93.30% | 91.30% |
| | 2000 ms | 97.32% | 93.53% | 93.75% | 90.18% |

Table 1. Accuracy as a function of Distractor Type and SOA by task in Experiment 1a and 1b.

containing WM content unrelated distractors (*"unrelated"*; Exp. 1a: *M* = 897.38, *SD* = 128.95; Exp. 1b: *M* = 887.45, *SD* = 115.73) and WM content related distractors ("*related*"; Exp. 1a: *M* = 918.125, *SD* = 136.70; Exp. 1b: *M* = 914.57, *SD* = 133.65) and were not included in further analysis.

Median response times were analyzed using a 2 (Distractor Type: *unrelated* or *related*) x 2 (Prime Type: *visual* or *verbal*) x 5 (SOA: *100ms, 300ms, 600ms, 1200ms,* or *2000ms*) mixed model repeated measures ANOVA, with Kenward-Roger adjusted degrees of freedom. Compound symmetry was assumed (all Mauchly's Tests of Sphericity were non-significant). For Exp. 1a there was a significant effect of Distractor

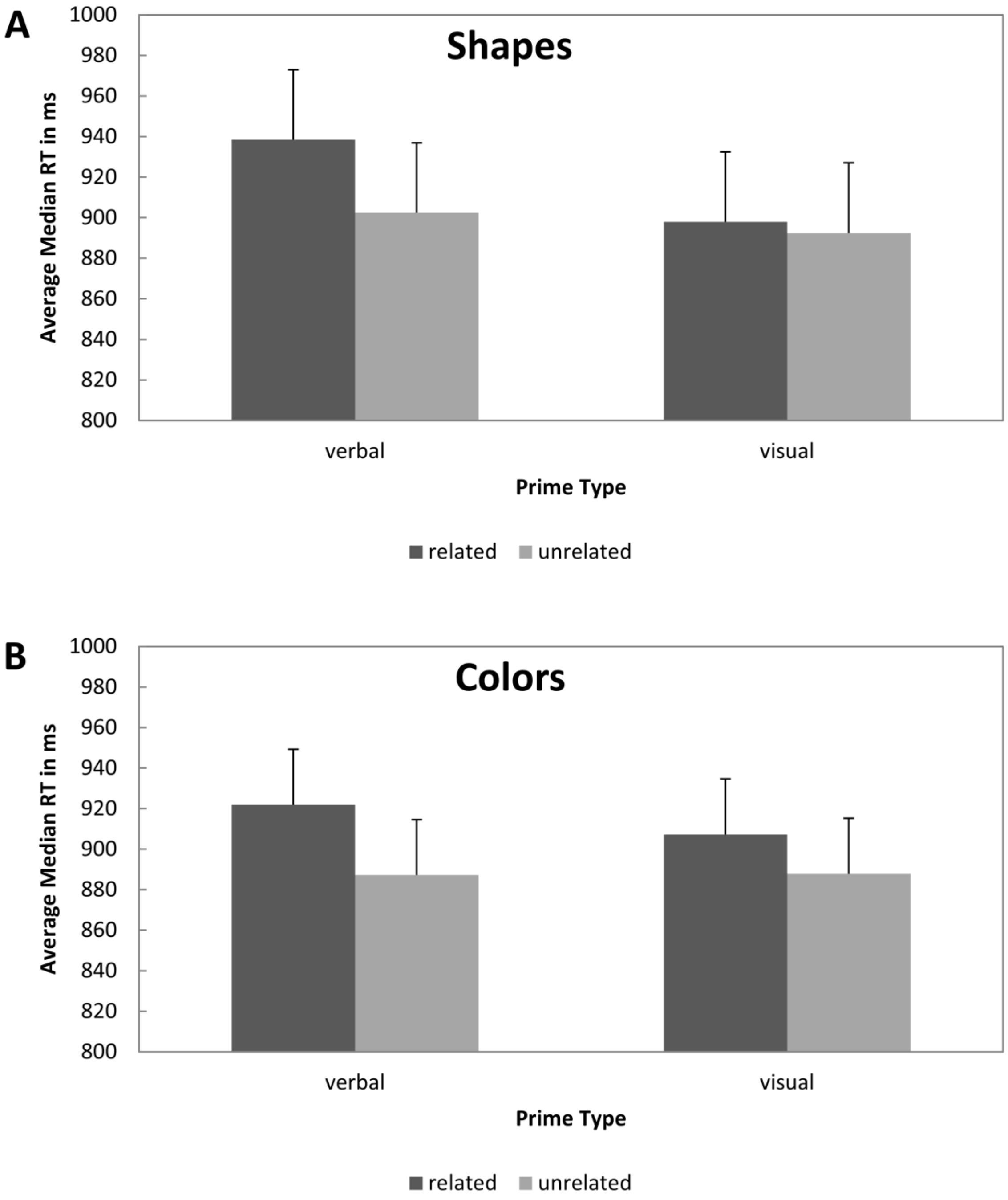


Figure 2. Average median response time for WM content *related* and *unrelated* distractors as a function of Prime Type (*verbal* or *visual*) for shapes (A; Exp. 1a) and colors (B; Exp. 1b). Error bars indicate standard error.

Type. Average median RT on trials containing WM content *related* distractors (*M* = 918.125, *SD* = 136.70) was slower than for trials containing WM content *unrelated* distractors (*M* = 897.38, *SD* = 128.95), *F*(1,209) = 5.05, *p* = .03. In addition, there was an effect of Prime Type. Trials containing a *visual* prime (*M* = 895.13, *SD* = 133.25) were faster than trials containing a *verbal* prime (*M* = 920.37, *SD* = 132.11), *F*(1,209) = 7.48, *p* < .01. Experiment 1b only showed the Distractor Type effect, with slower median RT for trials containing WM content *related* distractors (*M* = 914.57, *SD* = 133.65) compared to WM content *unrelated* distractors (*M* = 887.45, *SD* = 115.73), *F*(1,247) = 7.24, *p* < .01. No other effects were significant. No interactions were significant in either experiment.

## Discussion

The results show a clear attentional bias towards working memory content related distractors for both types of stimuli, colors and basic shapes. In addition, the results support the hypothesis for rapid emergence of the attentional bias towards WM contents for basic features. However, no difference in time course of attentional bias between colors and shapes was evident. Both colors and shapes capture visual attention, when held in working memory, even at the shortest SOA. This finding stands in contrast to Soto et al. (2005), who found no attentional effects for shapes. However, compared to Soto et al. this experiment utilized a longer cue presentation time (500ms vs. 105ms). It is possible that with shorter cue presentation time (e.g. 100ms) the initial capture effect would disappear selectively for shapes. Shorter cue times could potentially result in problems with processing of the verbal primes. In fact, Soto and Humphreys (2007) used cue times of 2000ms in their verbal cuing experiment. Our results suggest that even for

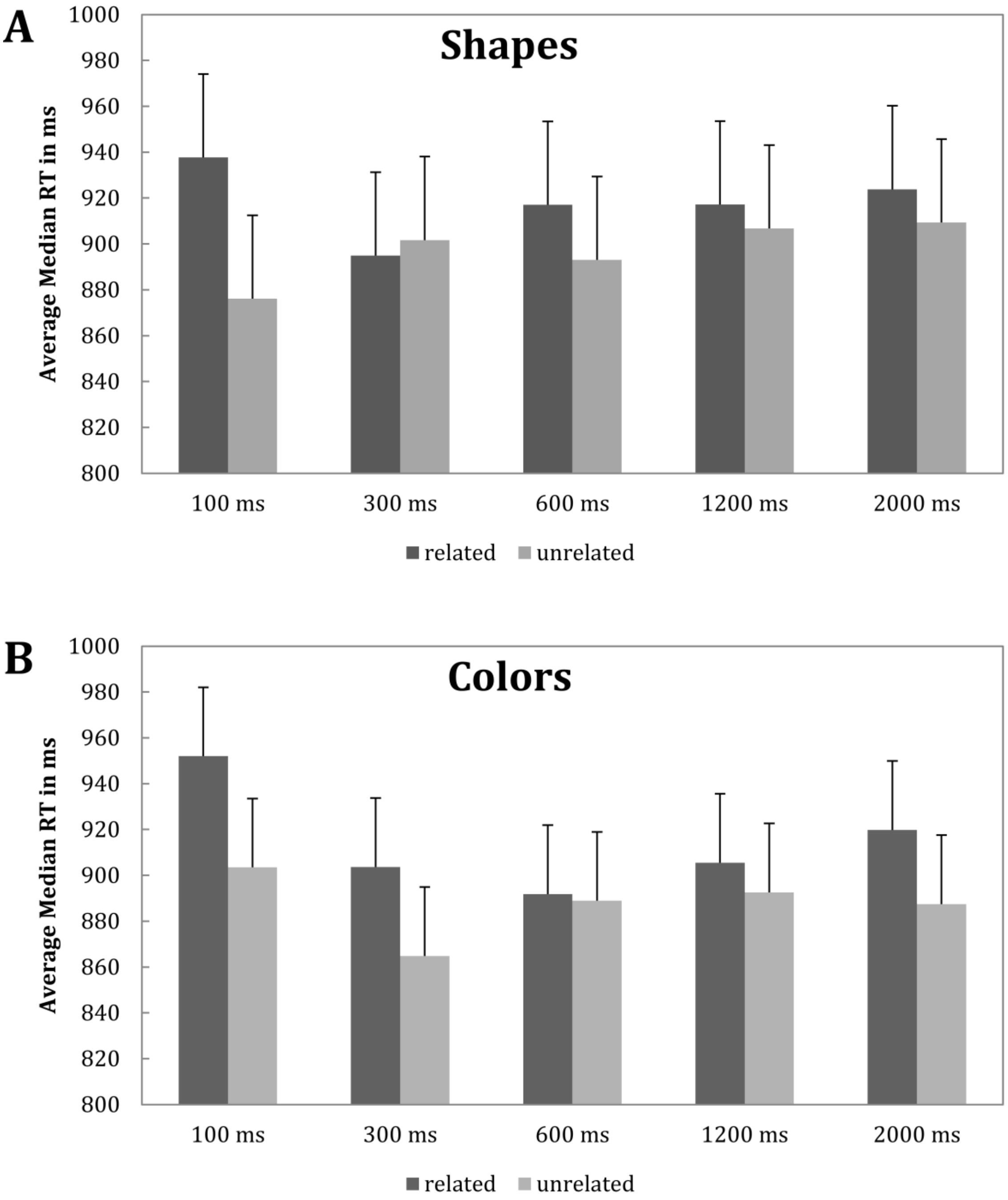


Figure 3. Average median response time in ms for WM content *related* and *unrelated* distractor trials, as a function of SOA in ms for shapes (A) and colors (B). Error bars indicate standard error.

verbal primes attentional capture of WM contents happens rapidly, within 600ms of initial WM content presentation (500ms cue presentation, 100ms SOA). It is possible that a differential time course effect for the two stimulus types was masked by the 500ms cue presentation time. Possibly both types of stimuli show attentional capture of WM contents visible at much shorter times, and a difference between the two could become apparent when looking at shorter cue presentation times. Note also that, even though the interaction was not significant, there seems to be only a minimal effect for shapes when primed visually. Soto et al. (2005), also used a visual priming paradigm. It is necessary to point out that while in their study the same prime shape was repeated as distractor, in the present study the distractor was a different exemplar form the shape category (see Appendix A). Possible reasons why no effect was found for this priming type are covered in the General Discussion section.

The absence of a Prime Type x Distractor Type interaction indicates that there was no difference for attentional bias towards WM contents between *verbal* vs. *visual* prime trials. Others argued that verbally encoded WM contents do not drive attentional capture. For example, Olivers et al. (2006) found attentional capture of WM contents only for difficult to verbalize material. They argued that the inability to verbalize WM contents, either due to stimuli that are difficult to verbalize, or by utilizing articulatory suppression, is required for attentional capture of WM contents. My findings indicate that this is not the case. In this experiment, WM content related capture was observable even when the WM content was a directly verbalized word prime. In fact, the effect of verbally presented primes is larger than for visually presented primes (Figure 2), and, for shapes, seems almost absent for visually primed trials (however, the interaction was *not* significant). The same attentional bias towards WM contents was found when using easy to verbalize *visual* stimuli (e.g. only one shade of red, or green for colors, or highly distinct geometric shapes, like oval, or rectangle). The ease of verbalization does not seem to be a determining factor for attentional bias towards WM contents. One explanation that could underlie the different findings is SOA time. Olivers et al. (2006) used a very long SOA of 3000ms. Given the long interval between initial prime presentation and WM related distractor display, it could be that for easy to verbalize stimuli sufficient time has elapsed to allow for attentional control processes to inhibit WM content related capture effects (Oberauer, 2002; Woodman & Luck, 2007), leading to a disappearance of the effect at very long SOAs. For difficult to verbalize stimuli the increase in WM capacity requirement for constant rehearsal of the stimuli leaves little capacity for these executive control processes, therefore displaying attentional capture effects even at very long SOAs (see also Lorat, 2008). Support for this explanation is also provided by Lavie (2005), who found impaired distractor inhibition under high executive WM load conditions, compared to low WM load. While the results of the present study do not provide statistical support for the idea that the attentional capture effect of WM contents decreases with time, as the interaction between Distractor Type and SOA was not significant, there seems to be a trend towards smaller effects for longer SOAs (Figure 4).

The finding that both types of primes suggest attentional capture of WM contents is also incompatible with the suggestion of Dombrowe et al. (2010) that, for their color stimuli, the capture effect disappears with longer cue/SOA intervals due to the conversion of the initial visual representation into a verbal representation, which they argue does not influence automatic allocation of visual attention. The findings obtained in this experiment argue against their conclusion, as even with initially verbally encoded stimuli attentional capture of WM contents was evident. Again, it is more likely that with time sufficient cognitive control can be exerted, so that any capture effects of WM contents disappear.

The hypothesis that *verbal* primes take longer to exhibit attentional capture effects, compared to *visual* primes, was not supported. Both types of primes showed attentional capture of WM contents even at the shortest SOA of 100ms, for both types of stimuli. A possible explanation is that the 500ms cue presentation time was sufficiently long for the feedback effect of verbal primes to exhibit influence on perception. A more thorough investigation of cue presentation times may be required to determine differences between both types of primes. However, one problem could be that with very short cue presentation times the stimulus energy, or the memory trace, could be too weak to influence attention. Olivers (2009) compared low stimulus energy objects (outlined circles) to high stimulus energy objects (filled circles) and found that the effect disappeared under low stimulus energy conditions. A similar effect could be evident when limiting perceptual input due to decreased cue presentation time. In addition, for *verbal* primes very short presentation times may hinder semantic processing, which could mask any effects of WM content related capture. However, a more thorough investigation of the unique effects of cue presentation time and SOA interval is warranted.

# CHAPTER III

# EXPERIMENT 2

This experiment was designed to compare the time course of visual and associative memory on WM content related attentional capture, within a single paradigm. Stimuli for this experiment are country names, with associated capital names and flags. This choice of stimuli allows for direct comparison of differences in time course for visual and semantic, associatively connected working memory contents. Participants either have to memorize a word prime (a country or capital name) or visual prime (flag). The color defined flags act as visual primes, which should show similar attentional influence, as the color primes in Experiment 1. Attentional capture effects of the WM content should be visible at very short SOAs, when flag stimuli act as both prime and distractor. Word primes, however, should initially show no influence on WM related capture, but should develop attentional bias at longer intervals. Semantically encoded primes should lack the initial activation advantage in visual perceptual areas. Feedback from WM to perceptual areas should be evident at later SOAs, as visual areas need to be pre-activated and semantic encoding might take longer to begin with. In addition there should be an effect of associative memory. When participants are cued with a word prime (e.g. country) it should take longer for the associate (e.g. capital) to show WM capture effects, than for the initial prime, as the associations have to be activated first. In addition it is possible that a cross modality effect can be found, namely that the cross modal associate will show slower top-down influence than the semantic associate; e.g. capital should show an effect at shorter SOAs than flag, when primed with country. For word primes it is likely that areas associated with letter processing (see Nobre, Allison, & McCarthy, 1994) are activated in addition to the higher order, abstract representation. Similar to the reasoning for the more visual prime, I assume that maintaining this activity will require less time than increasing activity in color related areas (Conway & Tsao, 2009) required for the flag stimuli. However, for the associate distractor, additional associate semantic connections need to be held active.

## Methods

### Participants

Based on estimated power (G*Power 3; Faul, et al., 2007) and literature review, 29 participants (9 male), age 18 – 32 (*M* = 19.79, *SD* = 2.59) were recruited via the University of Oklahoma research participation system for partial completion of course credit.

### Apparatus

The same apparatus as in Experiment 1 was used.

### Procedure and Stimuli

The countries used in this experiment, together with the associated capitals and flags are listed in Appendix B. The first part of this experiment served as a learning phase. Each country, with associated capital and flag was displayed on the center of the screen until key press. Participants were instructed to memorize each association. The order of presentation was randomized and each country was presented twice.

This was followed by a test phase, where each participant had to answer a selection of 15 randomly chosen questions. Participants were presented with a country, capital, or flag and were provided with a choice of three items from one of the two other categories. Participants had to answer via key press which item of the choice display belonged to the item in question.

The next part was the actual experimental phase. All displays consisted of a black background and, except flags, all stimuli and text were presented in white color. First, the prime was displayed for 1000ms. The prime could either be a word prime (*country,* or *capital*) or a flag prime. Participants were asked to memorize the prime for a later memory task. This was followed by a blank screen of variable SOA (*100ms*, *500ms*, *1000ms,* or *2000ms*). Next a display of four squares, presented with equal distances on an imaginary circle at the center of the screen, was shown. One of the squares could be a Landolt square (the target), containing an opening either at the top or the bottom. Participants had to indicate via arrow keys the location of the opening, as fast and accurately as possible. One of the other squares contained a distractor item (*country*, *capital*, or *flag*) in 50% of the trials (25% *related*, 25% *unrelated*). This stimulus array stayed visible until response, followed by a 500ms feedback display. After a blank screen of 500ms, a memory test display was shown. Participants had to answer if a displayed country, capital, or flag was associated with the prime. Again, this display stayed visible until response, followed by a 500ms feedback display. The next trial was preceded by a 500ms blank screen. The first block was a practice block, consisting of 15 trials, followed by 6 blocks of 72 trials each, for a total of 432 trials.

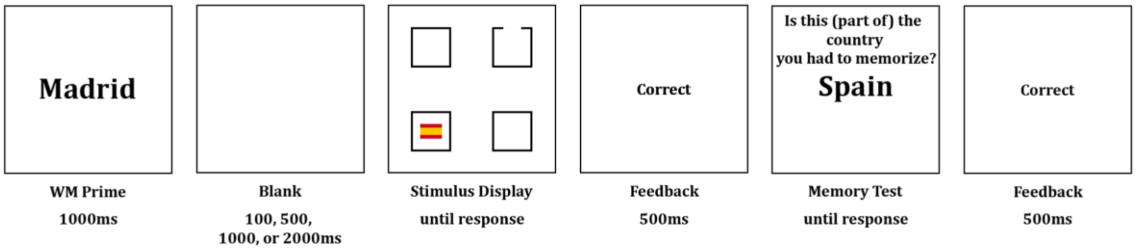


Figure 4. Example of the procedure in Experiment 2.

## Results

Accuracy in the initial learning test phase was high (*M* = .92, *SD* = .09). Subsequently only trials with correct responses on both test (target identification and memory test) were analyzed. Data from eight participants was excluded from data analysis due to low accuracy in the target identification task, the memory test, or both (accuracy < 75%). Accuracy was generally high, with a mean percentage of accurate trials of 98.19% for the target identification and 94.27% for the WM test (see Table 2).

Median RTs in trials without distractors (*M* = 628.48, *SD* = 90.55) were faster than in trials with WM content *unrelated* distractors (*M* = 725.75.84, *SD* = 175.88) and WM content *related* distractors (*M* = 726.35, *SD* = 176.32) and were excluded from further analysis.

As compound symmetry was not given (some Mauchly's Test of Sphericity were significant) median RTs were analyzed using a 4 (SOA: *100ms*, *500ms*, *1000ms*, or *2000ms*) x 3 (Prime: *Capital*, *Country*, or *Flag*) x 3 (Distractor Type: *Capital*, *Country*,

|  | Stimulus Display |  | Memory Test |  |
|---|---|---|---|---|
|  | Distractor Type |  |  |  |
| SOA | Related | Unrelated | Related | Unrelated |
| 100 ms | 98.41% | 98.06% | 95.77% | 94.00% |
| 500 ms | 98.59% | 98.24% | 94.71% | 93.30% |
| 1000 ms | 97.88% | 98.94% | 94.00% | 92.24% |
| 2000 ms | 97.71% | 97.71% | 95.94% | 94.18% |

Table 2. Accuracy as a function of Distractor Type and SOA by task in Experiment 2.

or *Flag*) x 2 (Distractor Relation: *unrelated* or *related*) repeated measures ANOVA, with Greenhouse-Geisser adjusted degrees of freedom. The main effect of SOA was significant, *F*(2.46, 46.86) = 4.15, *p* = .02, as was the main effect for Distractor Type, *F*(1.99, 37.89) = 4.44, *p* = .02 (Figure 5). Trials with *Flags* as distractors (*M* = 739.88, *SD* = 181.44) were slower than when a word acted as a distractor (*Capital*: *M* = 720.01, *SD* = 172.11; *Country*: *M* = 718.27, *SD* = 173.98), all *p*'s < .02. No other main effects were significant.

The two-way interaction between SOA x Prime was significant, *F*(4.35, 82.57) = 4.01, *p* < .01, as was Prime x Distractor Type, *F*(2.91, 55.31) = 4.80, *p* < .01. The SOA x Distractor Relation interaction did not quite reach significance with adjusted degrees of freedom, *F*(2.11, 40.06) = 2.72, *p* = .08 (Figure 6). With that in mind, post-hoc tests showed that the only significant difference between WM content *related* (*M* = 721.41) and *unrelated* distractors (*M* = 690.09) was at 500ms (*p* < .02).

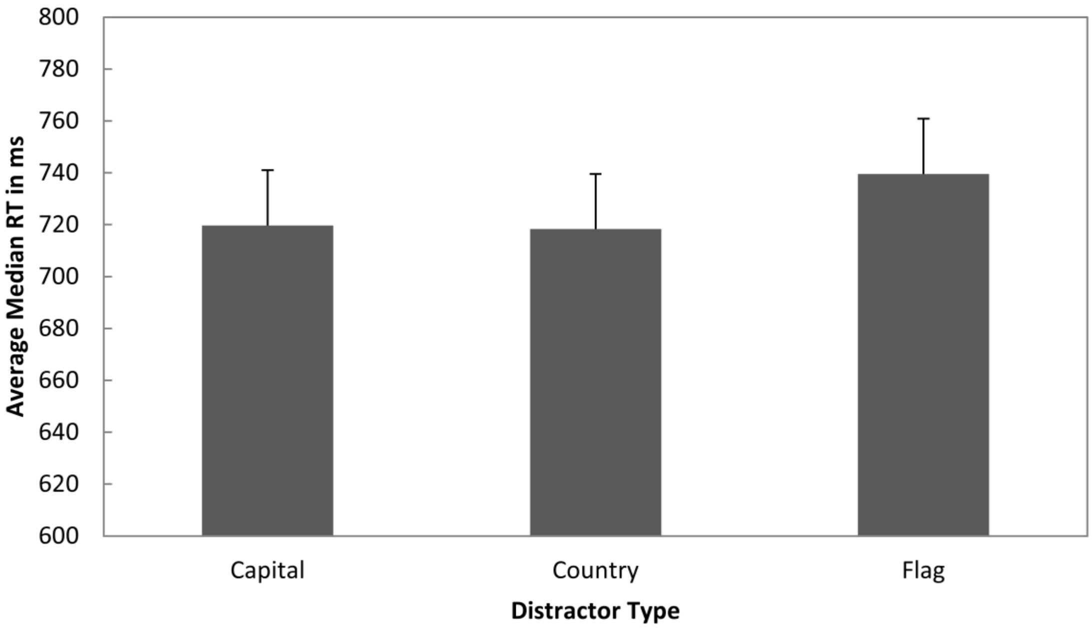


Figure 5. Average median response time in Experiment 2 as a function of Distractor Type. Error bars indicate standard error.

The three-way interaction between SOA x Prime x Distractor Type was significant, *F*(5.07, 96.33) = 2.28, *p* = .05, as was the SOA x Prime x Distractor Relation, *F*(4.38, 83.30) = 3.17, *p* = .02. The SOA x Distractor Type x Distractor Relation approached significance with adjusted degrees of freedom, *F*(3.90, 74.02) = 2.36, *p* = .06.

Lastly, the four-way interaction SOA x Prime x Distractor Type x Distractor Relation was significant, *F*(5.90, 112.13) = 2.76, *p* = .02. Post hoc tests to determine if there was a bias towards WM contents when the same Prime Type acted as a Distractor (Figure 7), showed only a significant attentional capture effect of WM contents for Country at 500ms (*related*: *M* = 810.67; *unrelated*: *M* = 695.29; p < .01) and the opposite effect, faster RT for the WM related distractor, for Flag at 2000ms (*related*: *M* = 730.64; *unrelated*: *M* = 824.55; p < .02).

## Discussion

The colored *Flags* showed the largest effect on RT when acting as a distractor, compared to the word distractors (*Capital*, and *Country*), displayed in white on a black background. This was expected, as the flags were the only colored stimuli and color singletons attract attention (Theeuwes, 1994). Surprisingly, there was no indication of attentional bias towards working memory content related distractors in this experiment, independent of SOA. Even though the interaction did not quite reach significance, the only indication of bias towards WM content related information was found at an SOA of

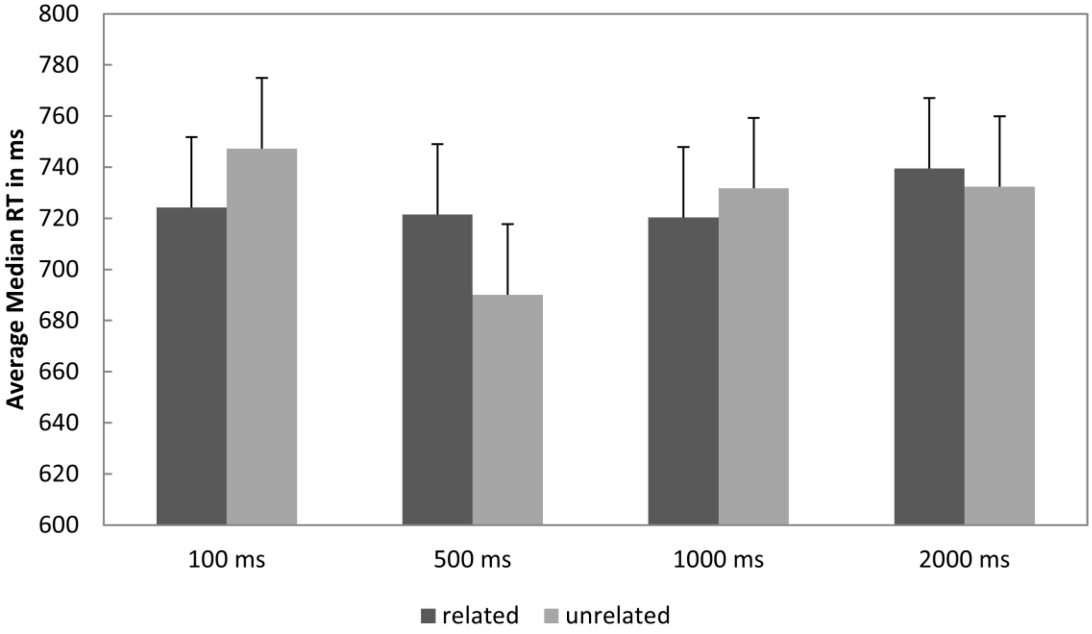


Figure 6. Average median response time in Experiment 2 as a function of SOA in ms, and Distractor Relation. Error bars indicate standard error.

500ms (Figure 6). When taking Prime Type and Distractor Type into account, attentional bias towards WM contents was only apparent for Country acting as both Prime and Distractor at an SOA of 1000ms (Figure 7).

The absence of any systematic attentional capture effects of WM contents stands counter to a multitude of studies on the topic, as well as against the results of Experiment 1. Even for the color stimuli in this experiment (flags) no attentional capture of WM contents was evident. As this experiment uses a novel type of stimuli in this paradigm, it is possible that properties of the stimuli are responsible for the lack of attentional capture for WM contents. One explanation could be that the stimuli were not strong enough to attract attention. For example Olivers (2009) suggested that under conditions of low stimulus energy no bias towards WM contents is found. As he used low stimulus energy objects for both the prime and distractors, it cannot be determined if the prime or the distractor is responsible for the absence of the attentional bias effect. It is reasonable to assume that low stimulus energy primes provide little activation in perceptual areas, therefore limiting the preactivation advantage. Similarly, it is possible that low stimulus energy distractors do not activate perceptual areas sufficiently to capture and attract attention. However, in the present experiment primes should provide sufficient stimulus energy, as for word primes (*Capital* and *Country*) the whole word has to be processed to extract the semantics of the prime, required for the memory test, while *Flag* primes were filled out color stimuli, very unlike the 1 pixel wide outline, non-filled circles used by Olivers (2009). On the other hand, when acting as a distractor, the words do not have to be processed. It is possible that the word distractors could be treated as

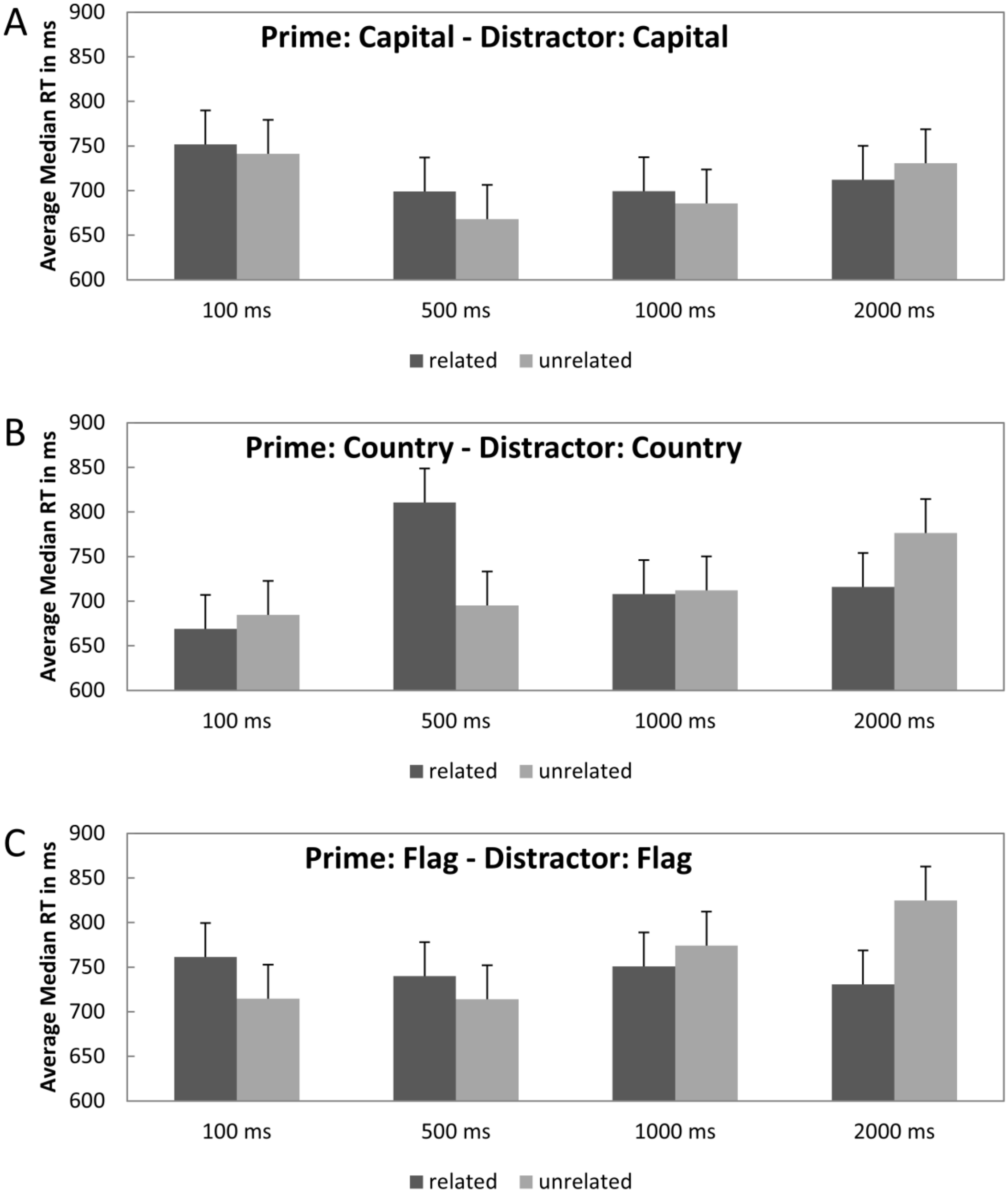


Figure 7. Average median response time in as a function of SOA, Prime Type and Distractor Type (*Capital*: A; *Country*: B; *Flag*: C) for working memory content *unrelated* and *related* distractors in Experiment 2. Error bars indicate standard error.

color distractors (white), therefore would not require semantic processing, and instead would just act as visual distractors. Research on the Stroop effect however suggests that word processing is automatic, even when detrimental to task performance (MacLeod, 1991), making this explanation unlikely. Additionally it would not explain why the effect was also absent for the color distractors (flags), especially in trials where the colored flags acted as both prime and distractor. Nor can it explain why the only attentional capture effect for WM contents was found when country names acted as both prime and distractor.

Olivers et al. (2006) argue that verbally encoded stimuli (e.g. *Capital* or *Country* primes), or easy to verbalize stimuli (*Flag* primes) do not show attentional capture of WM contents, and only visually encoded stimuli allow for this attentional bias. However, as was seen in Experiment 1a and 1b, verbal primes, as well as easy to verbalize stimuli both displayed attentional bias towards WM contents. Attentional capture of word primes has also been demonstrated in previous studies (Huang & Pashler, 2007; Moores, et al., 2003), making this explanation unlikely. Additionally, Dombrowe et al. (2010) argued that for easy to verbalize color stimuli an initial attentional bias effect is visible, but disappears with increasing SOA, as over time the visual representation is converted into a verbal representation. My results do not support this finding, as for color defined flags no indication of WM content related capture was found, even at very short SOAs.

A unique property of the flag stimuli used in the present study is that they are multi-colored, and additionally, for some of the flags the arrangement of the colors is a defining feature. For example the Russian flag contains the same colors as the French flag, but, besides a different order, colors are arranged horizontally, instead of vertically (Appendix B). To my knowledge, all studies that support attentional bias towards WM contents for colors to date utilize only single color stimuli. Multi-color stimuli may introduce additional mechanisms that hinder WM content related capture effects. In addition to multiple colors, flags may also be encoded in terms of shape. Most flags used in this experiment are separated into three rectangles, or contain a unique shape feature, like the stars in the Chinese flag, or the red circle of the Japanese flag. It is possible that encoding of some of the flag stimuli is shape driven, instead of color driven. However, while Soto et al. (2005) found no attentional bias effect for shape defined WM contents, they found such bias for conjunction stimuli, i.e. defined by both color and shape. As, at least for some flags, color needs to be encoded for correct identification, flag stimuli should be more similar to the conjunction condition. In addition, Experiment 1 provided support that shapes in WM by themselves are sufficient to guide visual attention automatically.

All in all the results of the present experiment suggest that there are other factors influencing attentional capture, which need to be determined. It is possible that the stimuli used in this experiment have unique features that do not support attentional capture of WM contents. While Olivers (2009) has provided a first systematic examination of what factors drive automatic capture of WM contents, it is necessary to expand and validate his findings to account for the lack of attentional bias of WM contents in the present experiment.

# CHAPTER IV

# EXPERIMENT 3

To my knowledge no article to date has provided a detailed analysis of the time course of attentional capture for WM content related *associative* memory. Experiment 3 is designed to allow for a detailed look at the effect of SOA on attentional capture for objects associated with semantic WM contents. Primes were selected from the University of South Florida Free Association Norms database (Nelson, McEvoy, & Schreiber, 2004), based on forward strength for three types of transportation related associates (*boat*, *car*, and *plane*).

Based on the spreading activation idea of LTM (Anderson, 1983), activation of the WM prime should spread towards the respective associate, which in turn should provide feedback to relevant perceptual areas. As objects do not receive direct activation from perceptual areas, I assume that for very short SOAs no difference in attentional capture between WM related and unrelated distractors should be evident. Rather, this effect should develop over time, as relevant feedback needs to be established first. Previous research found attentional capture of associates of WM contents for SOAs of around 800ms to 1000ms (Huang & Pashler, 2007; Moores, et al., 2003). At longer SOAs the effect could decrease again, due to the same inhibitory control mechanisms described above (Oberauer, 2002).

Primes in this experiment are verbal in nature, and should be encoded verbally, therefore any bias towards WM contents provides more evidence, in addition to the results in Experiment 1, that verbalization of the WM content is *not* a disqualifying condition for the attentional capture effect, counter to the suggestion by Olivers et al. (2006) and Dombrowe et al. (2010). It would also disagree with the assumption brought forward by Dombrowe et al. (2010), that transformation of an initial visually encoded prime into a verbally encoded prime explains the disappearance of the WM content related attentional capture effect, for their color primes.

## Methods

### Participants

Based on estimated power (G*Power 3; Faul, et al., 2007) and literature review, 36 participants (10 male), age 18 – 23 (*M* = 18.08, *SD* = 4.53)  were recruited via the University of Oklahoma research participation system for partial completion of course credit.

### Apparatus

The same apparatus as in Experiment 1 was used.

### Procedure and Stimuli

Connection strength information about the target and cue words selected from the University of South Florida Free Association Norms database (Nelson, et al., 2004) can be found in  Appendix C. The p was the same as in Experiment 2, except that the prime was always a word prime, randomly selected from the list of chosen words. The prime could be associated, with equal likelihood, with the target "*Car*", "*Boat*", or "*Plane*". The average forward strengths of words towards the associate was .56, .49, and .48, respectively (see Appendix D). The distractor could be a stylized image of a boat, car, or plane, shown in Appendix E. Distractors appeared in 25% of the trials, half of which

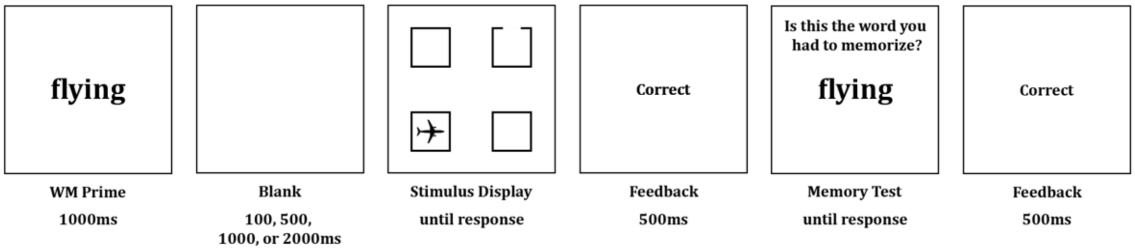


Figure 8. Example of the procedure in Experiment 3.

were associated with the WM prime. The first block was a practice block of 15 trials, followed by a total of 5 blocks, consisting of 96 trials each, for a total of 480 trials.

## Results

Only trials with correct responses on both test (target identification and memory test) were analyzed. Data from seven participants were excluded from data analysis. Five participants showed low accuracy in the target decision task, the memory test, or both (accuracy < 75%). Two participants showed an extensive speed vs. accuracy trade-off with median RT three standard deviations above the mean. Accuracy was generally high, with a mean percentage of accurate trials of 98.19% for the target identification and 94.27% for the WM test (see Table 3).

Trials containing no distractor (*M* = 621.73, *SD* = 63.03) were faster than trials containing WM content *unrelated* distractors (*M* = 674.46, *SD* = 108.13) and WM content *related* distractors (*M* = 676.37, *SD* = 102.73) and were not included in further analysis.

| | Stimulus Display | | Memory Test | |
|---|---|---|---|---|
| | Distractor Type | | | |
| SOA | Related | Unrelated | Related | Unrelated |
| 100 ms | 98.39% | 96.55% | 94.71% | 96.55% |
| 500 ms | 97.93% | 98.62% | 95.86% | 95.86% |
| 1000 ms | 97.47% | 97.93% | 95.17% | 94.71% |
| 2000 ms | 97.93% | 98.62% | 96.09% | 96.32% |

Table 3. Accuracy as a function of Distractor Type and SOA by task in Experiment 3.

Median response times were analyzed using a 2 (Distractor: *unrelated* or *related*) x 3 (Prime: *Boat, Car* or *Plane*) x 4 (SOA: *100ms, 500ms, 1000ms*, or *2000ms*) mixed model repeated measures ANOVA with Kenward-Roger adjusted degrees of freedom. As compound symmetry was not given (not all Mauchly's Tests of Sphericity were non-significant), an unstructured covariance structure was used. There was no main effect of SOA, $F(3, 26) = 1.92$, $p = .15$, or Distractor, $F(1, 28) = 0.09$, $p = .76$. The main effect of Prime was significant, $F(2, 27) = 3.6$, $p < .05$. Trials with a Prime associated with *Plane* ($M = 688.11$) were slower than trials associated with *Boat* ($M = 667.96$) or *Car* ($M = 670.18$), *p*'s < .03. There was no difference between trials containing Primes associated with *Boat* and *Car*, $p = .73$.

The two-way interaction between SOA and Prime was significant, $F(6, 23) = 7.76$, $p < .001$, as was the SOA x Distractor interaction, $F(3, 26) = 10.74$, $p < .001$ (Figure 9). Post hoc test indicated that median RT at 500ms for *related* distractors ($M = 667.34$) was faster than for *unrelated* distractors ($M = 701.8$), $p < .01$. This effect reversed at an SOA

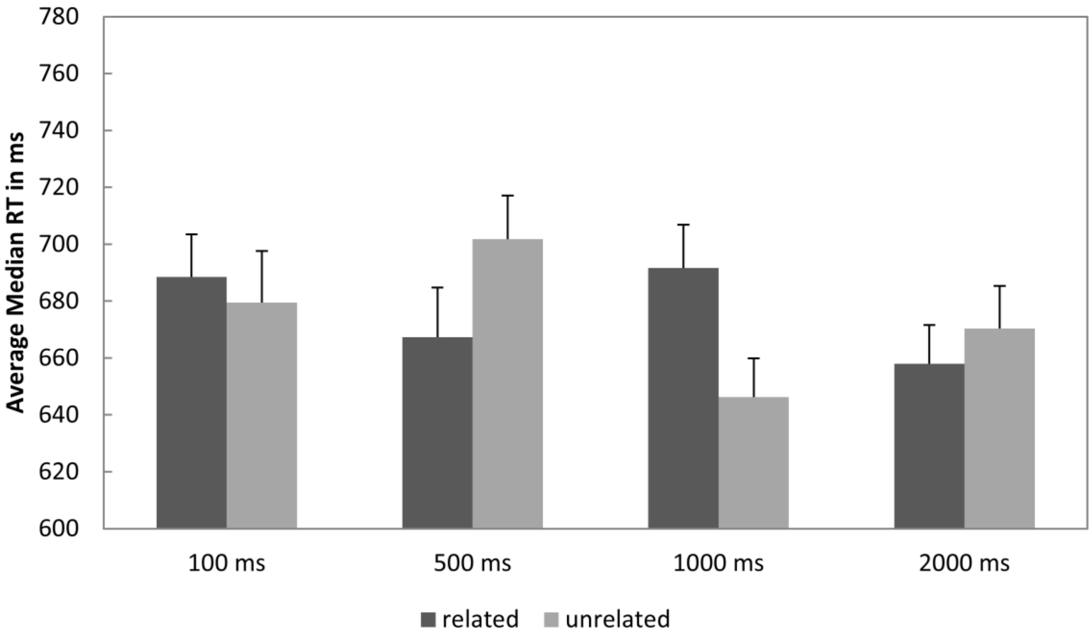


Figure 9. Average median response time in Experiment 3 as a function of SOA and Distractor Type. Error bars indicate standard error.

of 1000ms, where *related* distractor trials (*M* = 691.69) were slower than *unrelated* distractor trials (*M* = 646.23), *p* < .001.

The three-way interaction for Distractor x Prime x SOA was also significant, *F*(6, 23) = 3.87, *p* < .01. Post-hoc test showed the only significant difference for Primes associated with *Boat* was at an SOA of 1000ms, with *unrelated* distractor trials (*M* = 620.48) faster than *related* distractor trials (*M* = 657.69), *p* = .03 (Figure 10 A). Primes associated with *Car* (Figure 10 B) showed slower RT for *unrelated* distractor trials vs. *related* distractor trials at an SOA of 500ms (*M* = 707.41 vs. *M* = 651.16; *p* = .01) and 2000ms (*M* = 686.74 vs. *M* = 636.38; *p* = .01), and faster RT at an SOA of 1000ms (*M* = 647.21 vs. *M* = 689.91; *p* = .01). Primes associated with *Plane* (Figure 10 C) showed

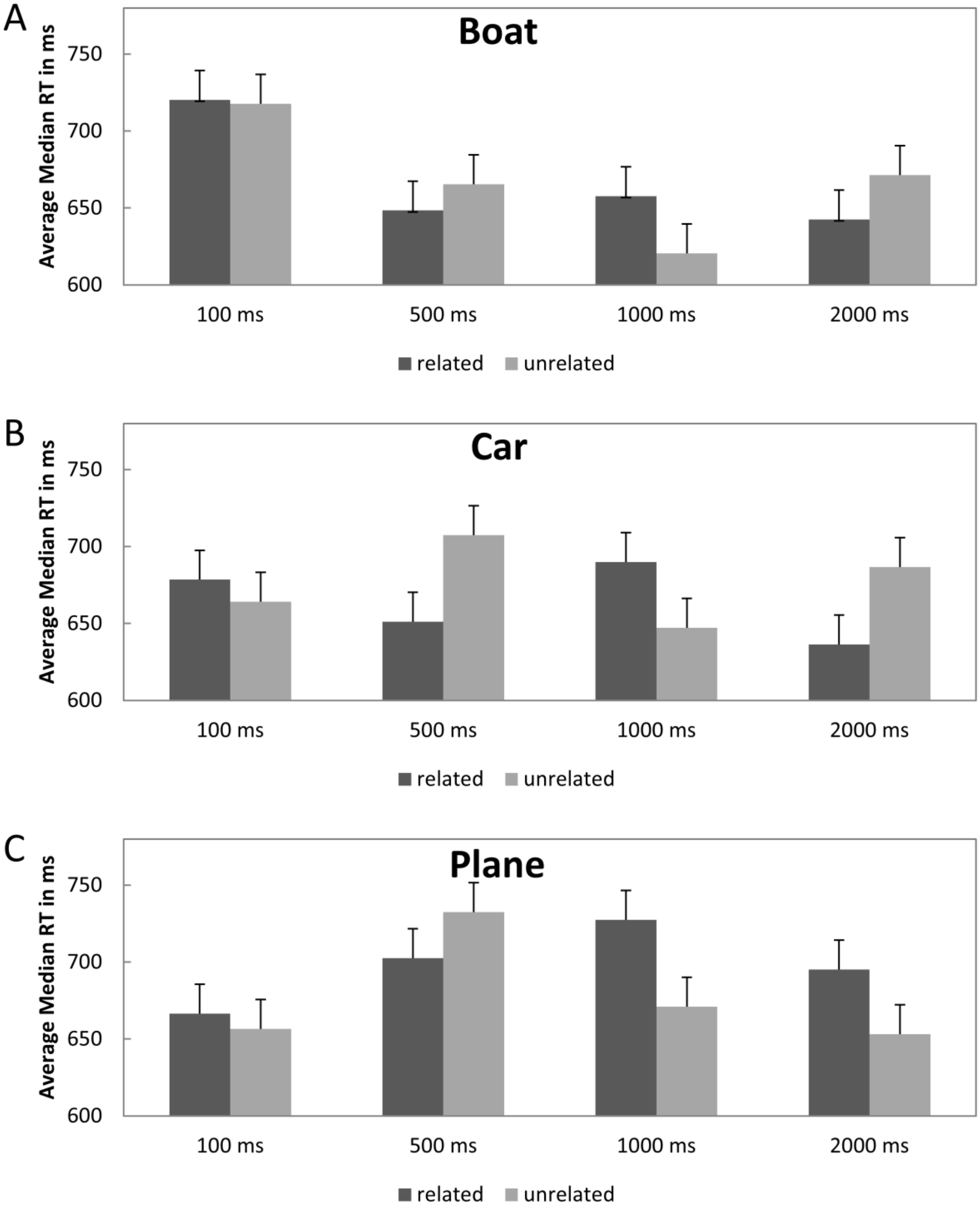


Figure 10. Average median response time in Experiment 3 as a function of SOA and Distractor, for Primes associated with *Boat* (A), *Car* (B), or *Plane* (C). Error bars indicate standard error.

faster RT for *unrelated* distractor trials vs. *related* distractor trials at an SOA of 1000ms ($M$ = 671.00 vs. $M$ = 727.47; $p < .01$) and 2000ms ($M$ = 653.10 vs. $M$ = 695.12; $p < .01$).

## Discussion

Independent of SOA there was no indication of attentional bias towards distractors associated with WM contents. When taking time course into account, the results support the hypothesis that, for associative memory, bias towards WM content related information develops over time. Attentional capture of distractors associated with WM contents was absent at the shortest SOAs and only became apparent at an SOA of 1000ms. This pattern was consistent across all three Prime associates. In addition, the finding that attentional bias towards WM content related information disappeared again at 2000ms supports the idea that, with sufficient time, executive control processes can be utilized, allowing for strategic attentional control.

A more detailed picture emerges when looking at the individual Prime associates. At very short SOAs there was no difference between *unrelated* and *related* distractors for either Prime associate. At 500ms there was a trend towards inhibition of *related* distractors, however only significantly so for *Car* related primes. Finally, at an SOA of 1000ms all three Prime associates showed the expected bias towards WM content related information. This effect persisted for an SOA of 2000ms only for *Plane* related primes. For both *Car* and *Boat* there was again a trend towards inhibition of information associated with WM contents, again only significant for *Car* related primes, showing faster RT for trials containing WM content related distractors. While the disappearance of the WM content capture effect was hypothesized, the reversal of the effect, faster RT for *related* distractor trials for *Car* primes at 500ms and 2000ms, was unexpected. It is not a unique finding, however, as similar results were reported by Woodman and Luck (2007), who found that participants were able to strategically allocate visual attention away from WM content *related* distractors, leading to an RT advantage for those trials compared to WM content *unrelated* distractor trials. They used an array of colored Landolt squares, where the same color could act as prime and distractor, while in this experiment prime and distractor were only associatively related and visually, as well as categorically distinct (words vs. images), leading to the suggestion that this strategic control is not limited to WM contents, but extends to information semantically associated with WM contents. It is not a generalized attentional control mechanism, as in that case no differences between WM content *related* and *unrelated* distractor trials would be expected. The effect seems to be confined towards information associated with WM contents. The suggestion that cognitive control over attentional allocation increases over time cannot explain why there was an RT advantage for *Car* related primes at 500ms, before the WM content bias effect was found.

While the time course of attentional allocation for *Boat* and *Car* related primes is comparable, *Plane* related prime trials showed a sustained attentional capture effect, at the longest SOA of 2000ms. While there is a trend toward decreasing attentional capture, the reversal of the effect, as evident for the other two primes, is not evident. It is possible that the same effect would have appeared at even longer SOAs. An alternative explanation could refer to the prototypicality of the distractor icon. A simple Google search confirms that while there are many common ways to stylize cars, or boats, the icon for plane used in this experiment, with slight variations, seems to be a more prototypical symbolic depiction. It could be that the icons have different connection strengths to the concepts they represent, leading to slightly different time course effects. However, it is necessary to point out that nevertheless there is great similarity between the results for the different prime associates, even with the longer evident WM capture effect for *Plane* primes.

The unique contribution of this experiment is that, for stimuli associated with WM contents, depending on SOA, very different types of results can be obtained. First, at very short SOAs and, depending on the stimulus, very long SOAs, there is no indication of bias towards stimuli associated with WM contents. Secondly, with increasing SOA the expected bias towards WM contents develops over time, appearing consistently in this experiment at 1000ms. Thirdly, with further increases in SOA this effect disappears again. Lastly this effect can even reverse at certain SOAs (500ms and 1000ms, for *Car* related distractors), suggesting WM related stimuli can display an inhibitory mechanism.

# CHAPTER V

# GENERAL DISCUSSION

The time course of attentional bias of working memory contents and working memory content related information has been the focus of little research interest. The purpose of the present studies was to investigate differences in time course of attentional bias towards WM contents for basic features and associative, semantic LTM contents. The results of Experiment 1 suggest that bias toward WM contents consisting of basic features, like color and shapes, is evident quickly, within 600ms of stimulus onset (500ms prime presentation, 100ms SOA). This effect is found independent of prime type. Both visual and verbal primes show attentional capture of WM contents at very short SOAs.

While the results of Experiment 2 did not show a consistent bias towards WM contents, it replicated the pattern in current literature, that not all studies find support for this attentional bias. This highlights the necessity to empirically determine which factors are sufficient and/or required to favor attentional capture of WM contents.

Experiment 3 investigated the time course of attentional capture of WM content associated memory. In support of my hypothesis, attentional bias was found at much later SOAs than for basic features (1000ms vs. 100ms). In addition, this experiment showed that depending on time course very different results relating to attentional bias can be obtained. Within the same experiment I found support for attentional bias towards WM content related information, the absence of this bias, as well as the opposite effect, inhibition of WM content related information, a bias *away* from WM contents. It is therefore necessary for any literature investigating the WM capture effect to take the time course of the attentional capture into account.

Taken together, the results support the argument, detailed in the introduction, for a differential time course of attentional capture of WM content related information, for basic visual features and semantically related LTM contents. The finding that basic features provide rapid attentional bias at very short SOAs follows the argumentation made in the introduction, that preactivation in early perceptual areas helps bias attention towards WM content related features (Desimone & Duncan, 1995). Basic features are thought to receive both, an activation advantage from preactivation as well as top-down feedback activation of associated perceptual areas, originating from WM. Stimuli semantically related to WM contents on the other hand lack the initial pre-activation in perceptual areas and depend on feedback activation from higher areas. Activation needs to spread from the encoded WM content to semantically related LTM contents, which then in turn provide activation feedback to early perceptual areas (Buffalo, et al., 2010; Naya, et al., 2001). This more complex activation network can be used to explain the longer time course until bias towards WM content related information is apparent in the distribution of visual attention.

The absence of attentional capture for WM contents in Experiment 2 was surprising. Even the color defined stimuli, flags, did not provide evidence for attentional bias towards WM contents. This highlights the important question of why some stimuli show attentional capture, while – even within the same paradigm – other stimuli do not. One difference of the flag stimuli is that they consist of multiple colors, compared to the single color stimuli commonly used in the attentional capture literature. Activation of multiple colors within one object might activate a broad range of color associated perceptual areas, which do not allow for pre-activation advantage of one color. In addition, as mentioned above, flags are not only defined through color, but also arrangement of the colors. This might add spatial information to the color stimuli, making the distinction between flags less dependent on color alone. All in all, the results of Experiment 2 highlight the importance for in depth analysis of what drives attentional capture of WM contents, and which stimulus features are required to find the attentional bias. While some work has begun in this direction (Olivers, 2009), the question remains mostly unanswered.

The results for attentional bias towards WM contents at very short SOAs, both for *verbal* and *visual* primes, in Experiment 1 stand in contrast to the findings of Olivers and colleagues (Dombrowe, et al., 2010; Olivers, et al., 2006), who argue that verbal encoding of stimuli removes any such effect. Compared to the experiments reported here, they used very long SOA intervals of 3000ms between prime presentation and the stimulus display. One possible explanation for the different results could be the idea that once primes are fully consolidated into WM they require less activation for maintenance, leading to a decreased feedback signal towards perceptual areas. Indeed, some studies have reported a decrease in activations in WM associated areas for maintenance compared to active manipulation of WM contents (D'Esposito, Postle, Ballard, & Lease, 1999) and initial encoding of WM contents (Woodward et al., 2006). In addition different areas are active for encoding versus maintenance of WM contents (Glahn et al., 2002). It may be that attentional bias towards WM contents follows an inverse U shaped pattern. Initially memory strength is low, and stimuli do not show attentional bias significantly different from WM content *unrelated* stimuli. With increasing consolidation into WM, activation in associated areas increases, influencing attentional selection, as suggested by Desimone and Duncan (1995). After the stimulus has been fully encoded and consolidated into WM and the stimulus now only needs to be maintained, activation decreases, leading to a decrease in attentional allocation towards the WM content. This may be accompanied by an increase in executive control over attention, so that the WM capture effect disappears again. This would also explain why Olivers et al. (2006) found attentional capture only for hard to maintain, easily confusable color stimuli (e.g. slightly different shades of green). Maintenance of these types of stimuli is necessarily more cognitively demanding, as even a slight variation in WM content representation makes the stimulus confusable with an alternative of the same category. While for easy to maintain colors (different colors) no such constant “surveillance” of the WM representation is necessary. While this mechanism could explain the supposed inconsistency in findings, research specifically designed to investigate these assumptions is necessary.

The small difference in RT between WM content related and unrelated distractor trials for visually primed shapes in Experiment 1 is initially surprising. One would expect similar effects as compared to verbally primed trials. However, note that, in this experiment, the shapes used as primes and the shapes used as distractors were only categorically similar, and not directly repeated (see Appendix A). It is possible that the preactivated perceptual areas showed only small overlap with the activation for the distractor, compared to when the same stimulus would have been repeated. Verbal primes, on the other hand may activate a wider range of perceptual areas, associated with the respective verbal representation of the shape. If we assume that connection strength is based on concurrent activation (Bliss & Collingridge, 1993; Teyler & DiScenna, 1987), it is likely that the conceptual representation of “triangle” is connected with a multitude of activation patterns representing triangles, while the actual visual “triangle” prime is only associated with a single activation pattern, that may overlap with other “triangle” activation patterns to varying degrees. A slightly smaller difference between RT for WM content related and unrelated distractor trials, for visual compared to verbal primes, albeit not as small as for shapes, was also found for colors. Again, different shades of a color were used as prime and distractor. However, colors are represented in a much small activation pattern than shapes. E.g. there are only three types of basic color receptors in the fovea and all perceivable color combinations are represented through a variation in activation amongst the three receptors. Early stages in visual cortex should reflect this pattern. Therefore we would expect that the difference in activation between different shades of a color is more observable in terms of extend of activation, rather than location of activation, while for shapes, location is a much more defining feature (e.g. line length, location of angle, etc.).

While the present series of experiments varied SOA intervals, cue presentation was held constant at 500ms and 1000ms. This was done to allow for sufficient time to process semantic primes. Decreasing presentation time may hinder encoding, and/or processing of semantics of the word primes, leading to confounded results. However, undoubtedly cue presentation time is also a major influencing factor in the time course of attentional bias towards WM contents, as prime processing is likely to start early after cue onset. To my knowledge no formal investigation of cue presentation times has been published to date. Decrease in cue presentation might lead to a decrease in encoding strength for the prime.  Olivers (2009) manipulated stimulus energy of the prime (but also items in the stimulus display), by using objects defined only by a narrow color outline. He found that in this case any WM content related capture effects disappeared. Similar results could be expected when decreasing stimulus energy due to limitation of presentation time, at least for visual primes. Note however, that attentional bias towards WM contents was found even for very short cue/SOA combinations for basic colors, but not shapes (Soto, et al., 2005).

In comparison to the early appearance of WM content related attentional capture for basic features, the effect required significantly more time for WM content associated stimuli. While at an SOA of 100ms no attentional bias towards WM content related information was visible, unlike for stimuli defined by basic features, the bias became apparent later, at 1000ms. As suggested in the introduction, spreading activation may underlie this difference in time course. Activation of the prime in WM spreads to associated, semantically related items. The strength of the spreading activation is thought to be determined by the degree as well as the distance of association. More loosely associated concepts should lead to smaller effects than closely associated concepts. Once these items become activated, they in turn should provide feedback activation towards perceptual areas, guiding attentional allocation. Further research could investigate how the degree or strength of association influences the time course and strength of the attentional bias effect. Closer degree of association would suggest a faster time course, while stronger association could lead to a stronger effect.

A surprising, but not novel effect (Downing & Dodds, 2004; Woodman & Luck, 2007) was the suggestion of an inhibitory mechanism in Experiment 3. I found evidence for faster RT for trials containing WM content *related* distractors compared to *unrelated* distractors. This suggests some kind of attentional control mechanism that can utilize

WM contents to allocate attentional resources. This finding exhibits the exact opposite pattern of results than expected based on the biased competition theory of visual attention (Desimone & Duncan, 1995). Even though the effect was only significant for one prime (*Car*), all primes showed a similar trend (Figure 10).

The inhibition effect could be due to strategic attentional allocation or automatic processes. In this experiment, as well as for Woodman and Luck (2007), items containing distractors could never contain the target. Therefore, participants could have strategically tried to inhibit the WM content for the target identification task. The pattern for faster RT for trials containing WM content related distractors before and after the expected WM content capture effect, could arise due to competition between the strategic attentional allocation, the avoidance of the WM content related information, and the automatic attentional allocation towards the WM content related information. Similarly to the above suggested inverse U shaped pattern, this would indicate that strategic allocation can override the automatic allocation, when the WM contents is not fully consolidated yet, or, for associated memory, has not activated the associated item sufficiently, yet. As activation of the WM content associated item increases, the automatic attentional allocation mechanism towards the WM content becomes stronger and is apparent in the behavioral pattern. When activation of the WM content associate decreases again, the strategic allocation again is sufficiently strong to drive attentional allocation. Alternatively, it could be that both mechanisms are automatic, but appear at different times. The idea that WM contents influence visual attention still holds true, but the relationship may be more complex than initially assumed.

# REFERENCES

Agam, Y., & Sekuler, R. (2007). Interactions between working memory and visual perception: An ERP/EEG study. *NeuroImage, 36*(3), 933-942. doi: 10.1016/j.neuroimage.2007.04.014

Anderson, J. R. (1983). A spreading activation theory of memory. *Journal of Verbal Learning and Verbal Behavior, 22*(3), 261-295. doi: 10.1016/S0022-5371(83)90201-3

Awh, E., & Jonides, J. (2001). Overlapping mechanisms of attention and spatial working memory. *Trends in Cognitive Sciences, 5*(3), 119-126. doi: 10.1016/s1364-6613(00)01593-x

Awh, E., Jonides, J., & Reuter-Lorenz, P. A. (1998). Rehearsal in spatial working memory. *Journal of Experimental Psychology: Human Perception and Performance, 24*(3), 780-790. doi: 10.1037/0096-1523.24.3.780

Awh, E., Vogel, E. K., & Oh, S. H. (2006). Interactions between attention and working memory. *Neuroscience, 139*(1), 201-208.

Beck, D. M., & Kastner, S. (2009). Top-down and bottom-up mechanisms in biasing competition in the human brain. *Vision Research, 49*(10), 1154-1165. doi: 10.1016/j.visres.2008.07.012

Biederman, I., Glass, A. L., & Stacy, E. W. (1973). Searching for objects in real-world scenes. *Journal of Experimental Psychology, 97*(1), 22-27. doi: 10.1037/h0033776

Bliss, T. V. P., & Collingridge, G. L. (1993). A synaptic model of memory: long-term potentiation in the hippocampus. *Nature, 361*(6407), 31-39. doi: 10.1038/361031a0

Broadbent, D. (1958). *Perception and comunication*: New York: Academic Press.

Buffalo, E. A., Fries, P., Landman, R., Liang, H., & Desimone, R. (2010). A backward progression of attentional effects in the ventral stream. *Proceedings of the National Academy of Sciences, 107*(1), 361-365. doi: 10.1073/pnas.0907658106

Buschman, T. J., & Miller, E. K. (2007). Top-Down Versus Bottom-Up Control of Attention in the Prefrontal and Posterior Parietal Cortices. *Science, 315*(5820), 1860-1862. doi: 10.1126/science.1138071

Chanon, V. W., & Hopfinger, J. B. (2008). Memory's grip on attention: The influence of item memory on the allocation of attention. *Visual Cognition, 16*(2), 325 - 340.

Chelazzi, L., Duncan, J., Miller, E. K., & Desimone, R. (1998). Responses of Neurons in Inferior Temporal Cortex During Memory-Guided Visual Search. *Journal of Neurophysiology, 80*(6), 2918-2940.

Chelazzi, L., Miller, E. K., Duncan, J., & Desimone, R. (1993). A neural basis for visual search in inferior temporal cortex. *Nature, 363*(6427), 345-347.

Chun, M. M., & Turk-Browne, N. B. (2007). Interactions between attention and memory. *Current opinion in neurobiology, 17*(2), 177-184. doi: 10.1016/j.conb.2007.03.005

Collins, A. M., & Loftus, E. F. (1975). A spreading-activation theory of semantic processing. *Psychological review, 82*(6), 407-428. doi: 10.1037/0033-295x.82.6.407

Conway, B. R., & Tsao, D. Y. (2009). Color-tuned neurons are spatially clustered according to color preference within alert macaque posterior inferior temporal cortex. *Proceedings of the National Academy of Sciences, 106*(42), 18034-18039.

D'Esposito, M., Postle, B. R., Ballard, D., & Lease, J. (1999). Maintenance versus Manipulation of Information Held in Working Memory: An Event-Related fMRI Study. *Brain and Cognition, 41*(1), 66-86. doi: 10.1006/brcg.1999.1096

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.

Desimone, R. (1998). Visual attention mediated by biased competition in extrastriate visual cortex. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences, 353*(1373), 1245-1255. doi: 10.1098/rstb.1998.0280

Desimone, R., & Duncan, J. (1995). Neural Mechanisms of Selective Visual Attention. *Annual Review of Neuroscience, 18*(1), 193-222. doi: 10.1146/annurev.ne.18.030195.001205

Dombrowe, I., Olivers, C. N. L., & Donk, M. (2010). The time course of working memory effects on visual attention. *Visual Cognition, 18*(8), 1089-1112. doi: 10.1080/13506281003651146

Downing, P. E. (2000). Interactions between visual working memory and selective attention. *Psychological Science, 11,* 467-473. doi: doi:10.1111/1467-9280.00290

Downing, P. E., & Dodds, C. M. (2004). Competition in visual working memory for control of search. *Visual Cognition, 11*, 689 - 703.

Duncan, J., & Humphreys, G. W. (1989). Visual search and stimulus similarity. *Psychological Review, 96*(3), 433-458. doi: 10.1037/0033-295x.96.3.433

Engle, R. W. (2002). Working Memory Capacity as Executive Attention. *Current Directions in Psychological Science, 11*(1), 19-23. doi: 10.1111/1467-8721.00160

Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods, 39*(2), 175-191. doi: 10.3758/bf03193146

Fuster, J. M., Bauer, R. H., & Jervey, J. P. (1985). Functional interactions between inferotemporal and prefrontal cortex in a cognitive task. *Brain Research, 330*(2), 299-307. doi: 10.1016/0006-8993(85)90689-4

Glahn, D. C., Kim, J., Cohen, M. S., Poutanen, V. P., Therman, S., Bava, S., . . . Cannon, T. D. (2002). Maintenance and Manipulation in Spatial Working Memory: Dissociations in the Prefrontal Cortex. *NeuroImage, 17*(1), 201-213. doi: 10.1006/nimg.2002.1161

Han, S.-H., & Kim, M.-S. (2004). Visual search does not remain efficient when executive working memory is working. *Psychological Science, 15*, 623-628. doi: doi:10.1111/j.0956-7976.2004.00730.x

Huang, L., & Pashler, H. (2007). Working memory and the guidance of visual attention: Consonance-driven orienting. *Psychonomic Bulletin & Review, 14*, 148-153.

Kane, M. J., Bleckley, M. K., Conway, A. R. A., & Engle, R. W. (2001). A controlled-attention view of working-memory capacity. *Journal of Experimental Psychology: General, 130*, 169-183.

LaBar, K. S., Gitelman, D. R., Parrish, T. B., & Mesulam, M. M. (1999). Neuroanatomic Overlap of Working Memory and Spatial Attention Networks: A Functional MRI Comparison within Subjects. *NeuroImage*, *10*(6), 695-704. doi: 10.1006/nimg.1999.0503

Lavie, N. (2005). Distracted and confused?: Selective attention under load. *Trends in Cognitive Sciences*, *9*, 75-82. doi: 10.1016/j.tics.2004.12.004

Lavie, N., & de Fockert, J. W. (2003). Contrasting effects of sensory limits and capacity limits in visual selective attention. *Perception & Psychophysics, 65*, 202-212.

Lavie, N., & de Fockert, J. W. (2005). The role of working memory in attentional capture. *Psychonomic Bulletin & Review, 12*, 669-674.

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*, 339-354. doi: 10.1037/0096-3445.133.3.339

Lorat, T. (2008). *Working Memory Capacity and Attentional Capture*. Unpublished master's thesis. University of Oklahoma. Norman, OK.

Lucas, C., & Lauwereyns, J. (2007). Selective working memory disables inhibition of visual features. *Experimental Psychology, 54*(4), 256-263.

MacLeod, C. M. (1991). Half a Century of Research on the Stroop Effect: An Integrative Review. *Psychological Bulletin, 109*(2), 163-203.

Malinow, R., Mainen, Z. F., & Hayashi, Y. (2000). LTP mechanisms: from silence to four-lane traffic. *Current Opinion in Neurobiology, 10*(3), 352-357. doi: 10.1016/S0959-4388(00)00099-4

Mayer, J. S., Bittner, R. A., Nikolic, D., Bledowski, C., Goebel, R., & Linden, D. E. J. (2007). Common neural substrates for visual working memory and attention. *NeuroImage, 36*(2), 441-453. doi: 10.1016/j.neuroimage.2007.03.007

Mishkin, M., Ungerleider, L. G., & Macko, K. A. (1983). Object vision and spatial vision: two cortical pathways. *TRENDS in Neurosciences, 6*, 414-417. doi: 10.1016/0166-2236(83)90190-x

Moores, E., Laiti, L., & Chelazzi, L. (2003). Associative knowledge controls deployment of visual selective attention. *Nature Neuroscience, 6*(2), 182-189. doi: 10.1038/nn996

Moores, E., & Maxwell, J. P. (2008). The role of prior exposure in the capture of attention by items in working memory. *Visual Cognition, 16*(5), 675-695.

Munneke, J., Heslenfeld, D. J., & Theeuwes, J. (2010). Spatial working memory effects in early visual cortex. *Brain and Cognition, 72*(3), 368-377. doi: 10.1016/j.bandc.2009.11.001

Naya, Y., Yoshida, M., & Miyashita, Y. (2001). Backward Spreading of Memory-Retrieval Signal in the Primate Temporal Cortex. *Science, 291*(5504), 661-664. doi: 10.1126/science.291.5504.661

Nelson, D., McEvoy, C., & Schreiber, T. (2004). The University of South Florida free association, rhyme, and word fragment norms. *Behavior Research Methods, 36*(3), 402-407. doi: 10.3758/bf03195588

Nobre, A. C., Allison, T., & McCarthy, G. (1994). Word recognition in the human inferior temporal lobe. *Nature, 372*(6503), 260-263. doi: 10.1038/372260a0

Oberauer, K. (2002). Access to Information in Working Memory: Exploring the Focus of Attention. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 28*(3), 411-421. doi: 10.1037/0278-7393.28.3.411

Olivers, C. N. L. (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), 1275-1291. doi: 10.1037/a0013896

Olivers, C. N. L., 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*, 1243-1265. doi: 10.1037/0096-1523.32.5.1243

Richter, T., & Zwaan, R. A. (2009). Processing of color words activates color representations. *Cognition, 111*(3), 383-389. doi: 10.1016/j.cognition.2009.02.011

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*, 248-261.

Soto, D., & Humphreys, G. W. (2007). Automatic guidance of visual attention from verbal working memory. *Journal of Experimental Psychology: Human Perception and Performance, 33*, 730-737.

Soto, D., & Humphreys, G. W. (2008). Stressing the mind: The effect of cognitive load and articulatory suppression on attentional guidance from working memory. *Perception & Psychophysics, 70*(5), 924-934. doi: 10.3758/pp.70.5.924

Soto, D., Humphreys, G. W., & Heinke, D. (2006). Working memory can guide pop-out search. *Vision Research, 46*(6-7), 1010-1018. doi: 10.1016/j.visres.2005.09.008

Soto, D., Wriglesworth, A., Bahrami-Balani, A., & Humphreys, G. W. (2010). Working memory enhances visual perception: Evidence from signal detection analysis. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 36*(2), 441-456. doi: 10.1037/a0018686

Teyler, T. J., & DiScenna, P. (1987). Long-Term Potentiation. *Annual Review of Neuroscience, 10*(1), 131-161. doi: doi:10.1146/annurev.ne.10.030187.001023

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. doi: 10.1037/0096-1523.20.4.799

Theeuwes, J., Atchley, P., & Kramer, A. F. (2000). On the time course of top-down and bottom-up control of visual attention. *Control of cognitive processes: Attention and performance XVIII*, 105-124.

Treisman, A. M. (1969). Strategies and models of selective attention. *Psychological Review, 76*(3), 282-299. doi: 10.1037/h0027242

Tsotsos, J. K. (1990). Analyzing vision at the complexity level. *Behavioral and Brain Sciences, 13*(3), 423-469.

Tsunoda, K., Yamane, Y., Nishizaki, M., & Tanifuji, M. (2001). Complex objects are represented in macaque inferotemporal cortex by the combination of feature columns. *Nature Neuroscience, 4*(8), 832.

Ungerleider, L. G., Courtney, S. M., & Haxby, J. V. (1998). A neural system for human visual working memory. *Proceedings of the National Academy of Sciences, 95*(3), 883-890.

Ungerleider, L. G., & Haxby, J. V. (1994). `What' and `where' in the human brain. *Current opinion in neurobiology, 4*(2), 157-165. doi: 10.1016/0959-4388(94)90066-3

van Zoest, W., Donk, M., & Theeuwes, J. (2004). The Role of Stimulus-Driven and Goal-Driven Control in Saccadic Visual Selection. *Journal of Experimental Psychology: Human Perception and Performance, 30*(4), 746-759.

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), 1436-1451. doi: 10.1037/0096-1523.32.6.1436

Williams, L. (1966). The effect of target specification on objects fixated during visual search. *Attention, Perception, & Psychophysics, 1*(5), 315-318. doi: 10.3758/bf03207398

Woodman, G. F., & Luck, S. J. (2004). Visual search is slowed when visuospatial working memory is occupied. *Psychonomic Bulletin & Review, 11,* 269-274.

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*, 363-377. doi: 10.1037/0096-1523.33.2.363

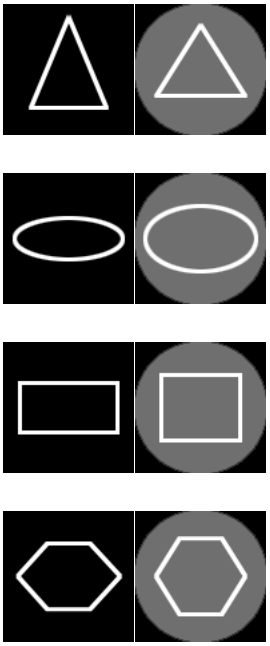
Woodman, G. F., Vogel, E. K., & Luck, S. J. (2001). Visual search remains efficient when visual working memory is full. *Psychological Science, 12,* 219-224. doi: doi:10.1111/1467-9280.00339

Woodward, T. S., Cairo, T. A., Ruff, C. C., Takane, Y., Hunter, M. A., & Ngan, E. T. C. (2006). Functional connectivity reveals load dependent neural systems underlying encoding and maintenance in verbal working memory. *Neuroscience, 139*(1), 317-325. doi: 10.1016/j.neuroscience.2005.05.043

# APPENDIX A

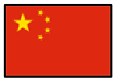
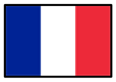
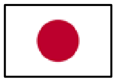
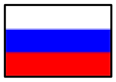
Examples of the stimuli for Experiment 1b

Cue Distractor



# APPENDIX B

Stimuli for Experiment 2

| **Country** | **Capital** | **Flag** |
|---|---|---|
| China | Beijing |  |
| France | Paris |  |
| Italy | Rome |  |
| Japan | Tokyo |  |
| Russia | Moscow |  |
| Spain | Madrid |  |

# APPENDIX C

List of the words used for Experiment 3, from the University of South Florida Free Association Norms database (Nelson, et al., 2004).

| Target | Cue | Forwardstrength |
|---|---|---|
| Car | Vehicle | 0.740 |
| Car | Dashboard | 0.740 |
| Car | Bumper | 0.647 |
| Car | Garage | 0.519 |
| Car | Driveway | 0.500 |
| Car | Drive | 0.480 |
| Car | Motor | 0.443 |
| Car | Mechanic | 0.432 |
| | | |
| Boat | Row | 0.739 |
| Boat | Oar | 0.695 |
| Boat | Sail | 0.589 |
| Boat | Dock | 0.559 |
| Boat | Sailing | 0.359 |
| Boat | Anchor | 0.325 |
| Boat | Harbor | 0.317 |
| Boat | Hull | 0.311 |
| | | |
| Plane | Airport | 0.757 |
| Plane | Pilot | 0.731 |
| Plane | Flight | 0.669 |
| Plane | Stewardess | 0.510 |
| Plane | Flying | 0.434 |
| Plane | Passenger | 0.314 |
| Plane | Co-Pilot | 0.236 |
| Plane | Navigator | 0.167 |

# APPENDIX D

Mean, minimum, and maximum forward strength for each of the target used in Experiment 3

| **Target** | **Mean** | **Min** | **Max** |
|---|---|---|---|
| Car | 0.563 | 0.432 | 0.740 |
| Boat | 0.487 | 0.311 | 0.739 |
| Plane | 0.477 | 0.167 | 0.757 |

# APPENDIX E

Distractors in Experiment 3