Examining the Nature of the Relationship Between Working Memory and Attention

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DEDICATION

This is dedicated to my family. Thank you for your enduring love and support through this journey, I could not have done it without all of you.

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LIST OF ABBREVIATIONS

CDA	Contralateral Delay Activity
IRB	Internal Review Board
OSPAN	Operation Span Task
SPCN	Sustained Posterior Contralateral Negativity
VA	Visuospatial Attention
WM	Working Memory
WMC	Working Memory Capacity

ABSTRACT

EXAMINING THE NATURE OF THE RELATIONSHIP BETWEEN WORKING MEMORY AND ATTENTION

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Working memory (WM) and visuospatial attention (VA) are both cognitive constructs that are related to the processing of relevant information. While these processes are capable of functioning independently, there is significant evidence suggesting a relationship between the two. However, the exact nature of this relationship is not well understood, and no testable hypotheses have been advanced.

In this dissertation, three experiments were conducted in an effort to uncover the nature of the relationship between WM and VA. It was hypothesized that when WM and VA are simultaneously deployed, a new process is formed (an integrated view). Based on this hypothesis, it was predicted that this new process would operate using the shared resources of WM and VA. This hypothesis was compared against the parallel view, which stated that WM and VA are separate processes that simply interact. The parallel view would not predict processing resources to be shared between WM and VA. The three experiments were designed to provide converging evidence to support one of these views by targeting different aspects of WM and VA and using various measurement techniques.

Results showed support for the integrated view. Specifically, it was demonstrated that manipulations in either WM or VA resulted in graded changes in the other process. This suggests a sharing of resources between the two processes, as would be expected if WM and VA had integrated to form a new process. The parallel view would predict that manipulations in either WM or VA would only have resulted in broad changes in the other process, indicative of a lack of resource sharing. These findings were demonstrated in all three experiments. First, it was shown that manipulating WM load resulted in differences in the effect of the timing of attentional deployment on behavioral performance. Second, manipulations in WM load were associated with different attentional distributions. Finally, the constriction of attention resulted in different relationships between working memory capacity (WMC) and the ability to filter out distracting information.

This range of evidence provides strong empirical support for the hypothesis that WM and VA form a new process when simultaneously deployed. Current models of WM and VA do not make predictions regarding the nature of the relationship between the two processes. Thus, should these findings be replicated, models of WM and VA will need to be modified accordingly.

1. INTRODUCTION

Visuospatial attention (VA) and working memory (WM) are fundamental processes of cognition. WM and VA must often both be used for the effective completion of a range of tasks—from making dinner to monitoring remotely piloted aircrafts—rendering the understanding of the nature of their relationship critical. WM is generally agreed to be the process by which currently relevant information in the environment is briefly stored and updated (e.g., Baddeley, 2007; Cowan 1999). Attention is a general term referring to the ability to identify and focus processing power on only the most relevant of stimuli and encompasses a variety of sub-fields (i.e., vigilance and sustained attention; e.g., as reviewed in Parasuraman, 2000). In VA these responsibilities only apply to visual stimuli. Interactions between these two processes have been reported (e.g., Awh, *et al.*, 1998; Clarke, 2010; Downing, 2000; Engle, 2002; Vogel, *et al.*, 2005; LaBar & Gitelman, 1999; Greenwood, Fossella, & Parasuraman, 2005; Greenwood, Lin, Sundararajan, Fryxell, & Parasuraman, 2009; Parasuraman, Greenwood, Kumar, & Fossella, 2005), the nature of which has yet to be firmly established. Importantly, there are no testable theories on this relationship.

Not only is the relation between VA and WM poorly understood, no testable hypotheses of the relation have been advanced. The two most widely accepted models of WM are the multicomponent (reviewed in Baddeley, 2007) and embedded processes (Cowan, 1999) models. These models differ in that the multicomponent model views WM as composed of a series of specialized sub-systems while the embedded process model views WM more of an emergent property. Both models include a substantial role for VA within the realm of WM. However, neither model makes testable predictions about the relation of these processes.

The conceptual overlap in the definitions of WM and VA are a reflection of the substantial empirical evidence that although WM and VA are capable of operating independently, they are also functionally related. For example, it has been demonstrated that there are cortical regions that are uniquely activated by WM or VA, as well as areas of conjoint activation (LaBar & Gitelman, 1999). Cognitive genetic research also provides supporting evidence. Specifically, when WM is manipulated, performance is associated with variation in a gene affecting the dopaminergic system (DBH), while when VA is manipulated, performance is associated with variation in a gene affecting the cholinergic system (CHRNA4; Greenwood, Fossella, & Parasuraman, 2005; Parasuraman, Greenwood, Kumar, & Fossella, 2005). However, the effect of the constriction of the attentional focus on WM task performance is affected by the interaction between two genes, CHRM2 and CHRNA4, which encode receptors in the muscarinic and nicotinic cholinergic systems, respectively (Greenwood, Lin, Sundararajan, Fryxell, & Parasuraman, 2009). Together, the findings of these behavioral genetic studies suggest that VA and WM are separate systems that can interact, with WM governed by the dopaminergic system, VA by the cholinergic system, and their simultaneous use by two cholinergic sub-systems. Electrophysiological studies also provide evidence in favor of WM and VA being separate but integrated processes. It was recently discovered that brain wave activity occurring during the delay period of a WM task is capable of indexing both VA (Clarke, *et al.*, 2010) and WM load (e.g., Klaver, Talsma, Wijers, Heinze, & Mulder, 1999; McCullough, Machizawa, & Vogel, 2007; Ruchkin, *et al.*, 1997), with the polarity of this activity dependent on whether WM (e.g., Ruchkin, *et al.*, 1997; Klaver, *et al.*, 1999; McCollough, *et al.*, 2007), VA (Clarke, *et al.*, 2010), or both is manipulated (Clarke, *et al*., 2010). In summary, a diverse array of tasks and measures suggest that WM and VA are dissociable when deployed in isolation, but when deployed together, appear to have a strong relationship, leading to the hypothesis that an integrated cognitive process may emerge when they are simultaneously deployed.

Hypothesis. We advanced the hypothesis that when WM and VA are invoked simultaneously by task demands, a new, integrated process emerges. This new process would therefore operate on the processing resources typically allocated to WM and VA individually. Should this occur, changes in performance that would result from taxing the resources of one of these processes could be overcome through the use of the resources typically allocated to the other process. This would suggest that manipulations in one process would result in graded changes in the other. The alternative hypothesis argues that WM and VA are parallel processes that interact at various points but are not integrated. The parallel view predicts that the there is no sharing of resources and therefore manipulation of one process is only capable of causing discrete changes in the other. Regardless of whether the integrated or parallel view is supported, the results of this study will have ramifications for the current models of WM and VA and the ability to predict performance on tasks requiring both processes.

This dissertation tested the aforementioned hypothesis through studies that examined the aspect(s) of stimulus processing affected by VA, manipulations of the distribution of attention, and the ability of individuals with high and low working memory capacity (WMC) to filter out distracting information. These studies used both behavioral and neurophysiological measures of performance.

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Visuospatial Attention (VA)

Visuospatial attention (VA) is the cognitive process by which pertinent information is targeted for enhanced processing. VA can be directed to target stimuli through exogenous or endogenous cueing at multiple time points in the processing stream, with the consequent enhancement in processing dependent upon both the attentional distribution and the difficulty/number of tasks being concurrently performed.

ORIENTING PROCESSES

VA can be directed towards a particular stimulus via either endogenous or exogenous methods. Endogenous attentional orienting (i.e., top-down processing, executive attention, or attentional control) implies that VA is directed towards a particular stimulus as a result of internally derived goals. These goals are often the result of cues that provide information regarding the location or nature of pertinent information. Using this method allows attention to be directed towards a particular stimulus for some duration. Exogenous orienting (or bottom-up processing) refers to the direction of VA based upon the stimulus such that attention is captured reflexively. For example, the sudden onset of a visual cue less than 100ms prior to a stimulus will cause VA to be directed towards that stimulus (e.g., Müller & Humphreys, 1991). Exogenous orienting results in brief shifts of VA (approximately 100-200ms). While both endogenous and exogenous orienting result in similar strength attentional effects, they differ in both the duration of these effects and their underlying mechanisms. The short duration of exogenous cueing was optimal for the experiments in this dissertation given that the paradigms needed extended time to heighten integration. While attention can be cued in multiple ways the most effective cuing method is dependent upon the paradigm used and the processes being examined.

EFFECTS OF TASK DIFFICULTY

Task difficulty plays an important moderating role in the effects of VA. Task difficulty refers to both the difficulty of a single task as well as a number of tasks concurrently performed. The amount of processing that unattended stimuli receive is dependent upon the difficulty of processing the attended target (Lavie, 1995). If one task is identified as the primary task, VA will be directed to that task at the expense of the other task (see Kramer, 1990 for a review; Prinzel, Freeman, Scerbo, Mikulka, & Pope, 2003). This has been demonstrated physiologically through the use of the P300—an ERP component thought to measure the distribution of processing resources in concurrent tasks as well as indexing variations in workload during single tasks (Wickens, Kramer, Vanasse, & Donchin, 1983). The P300 amplitude elicited by a secondary task decreases as the difficulty of the primary task increases, while the P300 amplitude elicited by the primary task increases with increasing task difficulty on the primary task (see Kramer, 1990 for a review; Prinzel, Freeman, Scerbo, Mikulka, & Pope, 2003). The results of these studies suggest that task difficulty modulates the ability of VA to enhance performance.

TIMING OF ATTENTIONAL DEPLOYMENT

An important factor in determining the effect of VA is the point at which it is deployed in the processing stream. Although it was originally thought that VA was only capable of exerting effects during a discrete early stage of processing (e.g., Broadbent, 1958) it is now widely accepted that it can exert effects on multiple stages of processing, both early and late (Lavie, 1995). However, it is hypothesized here that the effects of VA are able to propagate through the stages of WM processing following its deployment.

The effects of the timing of the deployment of VA on performance have been a topic of interest for many years. Early theories of VA either postulated that it acted early or late in the processing stream. In the early selection theory, VA was claimed to operate during encoding as a way to limit the items that are permitted access to further processing including memory (Broadbent, 1958). In late selection theory VA was claimed to act as a filter (J. A. Deutsch & Deutsch, 1963)

Evidence for both of these theories can be found in the attentional blink paradigm. In these studies, participants must respond to two stimuli presented in rapid succession. Interestingly, there is a period of several hundred milliseconds after the presentation of the first stimulus during which responses to the second stimuli are impaired (e.g., Broadbent & Broadbent, 1987; Chun & Potter, 1995; Duncan, *et al.*, 1994; Reeves & Sperling, 1986). This effect is termed the attentional blink. One explanation of the attentional blink is that it is the result of capacity limitations within WM, such that the second stimulus is properly encoded but does not gain access to WM, suggesting that attention can operate late in the processing stream (e.g., Treisman, 1964). Alternatively, the attentional blink could be the result of a bottleneck during encoding, which would support the view that attention acts early in the processing stream (e.g., Broadbent, 1982; Deutsch & Deutsch, 1963; Awh, Vogel, & Oh, 2006).

While both of the early and late views of VA provide theoretically plausible explanations for the attentional blink there is also empirical evidence to support them. For example, it has been shown that the attentional blink is instructionally dependent, such that if participants are told to ignore the first stimulus, then their responses to the second stimuli are not impaired (Raymond, *et al.*, 1992). This indicates that endogenous orienting, which occurs early in the processing stream, as was described earlier, plays an important role in WM processing. Additionally, the generators of P1 and N1 components are sensitive to WM and also influenced by attention-related feedback within 100ms of stimulus onset (Foxe & Simpson, 2002; Yago, Duarte, Wong, Barceló, & Knight, 2004). Support for the ability of attention to affect later stages of processing can be found in neurophysiological evidence, which suggests that stimuli thought to be suppressed by the attentional blink are processed even if this is not manifested behaviorally. The amplitude of the N400 component, which is considered an indicator of semantic congruity between a target stimulus and context, is similar both inside and outside the attentional blink (Luck, *et al*., 1996) and the amplitude of the P1 component (i.e., an index of early perceptual processing) is unaffected by the attentional blink (Vogel, *et al.*, 1998). The amount of evidence supporting attentional effects occurring both early and late in the processing stream suggests that attention is capable of exerting effects at multiple points during WM processing. In the context of the hypothesis advanced here, the findings that VA can operate at multiple points in the processing steam is important because it provides a basis for the feasibility of the prediction of the integrated view that the effects of VA to propagate through all stages of WM processing following its deployment.

More direct evidence of the ability of VA to affect WM processing at multiple time points arises from studies directly comparing the effects of deploying attentional cues prior to or following target presentation. Previous work has shown that pre- and post-cues produce similar behavioral effects, with enhanced behavioral performance observed when attentional cues are used, regardless of whether they are deployed before or after stimulus presentation (Griffin & Nobre, 2003). Interestingly, other literature demonstrates that an electrophysiological component, the N2pc, changes in polarity depending upon whether VA is deployed prior to or following a stimulus. This was interpreted as suggesting that after a stimulus has been encoded VA is directed towards the integrated object, whereas if VA is deployed prior to encoding, it is directed towards object features (Astle, Scerif, Kuo, & Nobre, 2009). These studies provide support for the fluid nature of VA. These results also show that the timing of the deployment of VA results in changes in the polarity of an electrophysiological component during a WM task. It is suggested that this may imply that VA is capable of perpetuating its effects into phases of WM processing following its deployment.

ATTENTIONAL DISTRIBUTION

The attentional distribution can be a determining factor in how VA interacts with any given environment. While there have been multiple observations concerning the shape and properties of this distribution, four have garnered substantial support—with one emerging as the most likely distribution based on the literature.

Early observations of the attentional distribution led to it being described it as a spotlight, with information optimally extracted from one area of focus and an increasingly diminished capability for processing at locations outside this focal area (Posner, Snyder, & Davidson, 1980). However, this observation is not consistent with two important recent findings: a) background information that is not explicitly relevant to the task of interest may have an important role in maintaining the mental representation of the target image during WM tasks (Greenwood, Lambert, Sunderland, & Parasuraman, 2005) and b) some studies have noted regions of suppression in areas surrounding the focus of attention (e.g., Bahcall & Kowler, 1999; Carr & Dagenbach, 1990; Cutzu & Tsotsos, 2003; Eriksen, Pan, & Botella, 1993; Kim, *et al.*, 1999).

The second observation, the zoom lens, incorporates all the aspects of the spotlight observation, with the added tenet that the size of the area from which information is optimally extracted can be modulated (Eriksen & St. James, 1986; Eriksen & Yeh, 1985). In other words, when attention is cued to a particular visuospatial location, it must be scaled to properly utilize attentional resources. Importantly, this observation does not include a provision that allows for attentional capacity to be modulated with the size of the area of focus, suggesting that processing speed is slowed when the area inside the attentional focus is increased. The dynamic scaling of attention proposed by this theory has found support in the neuroimaging literature. During "zoom in" conditions, or those in which attention is tightly constricted, the intraparietal sulcus is activated and when attention is "zoomed out" the right inferior frontal gyrus is activated (Q. Chen, Marshall, Weidner, & Fink, 2009). The finding of areas that are uniquely associated with "zoom in" or "zoom out" conditions suggests that zooming in and out constitute separate processes, lending support to the view that VA is a dynamic process and not just a spotlight. While this observation is more capable than the spotlight to account for recent findings it, like the spotlight theory, does not account for regions of suppression and suggests that ground information would be unlikely to benefit behavioral performance.

Another observation concerning the attentional distribution is the gradient, which predicted that stimuli that fall within the spotlight of attention but are not the focus of attention receive a lower priority for processing (LaBerge & Brown, 1989). This effect is best demonstrated by a task involving a string of five letters. On half the trials participants focused on only one letter and on the other half they focused on the entire word. Following the presentation of the first string of letters a second string appeared and participants were asked to respond to a particular letter that could be located at any of the five positions. It was found that when participants focused on the word they were quicker to respond to the target letter than when they focused on the letter (LaBerge, 1983). Additionally, it has been shown that the steepness of the gradient is dependent on task variables. The gradient falls off more steeply over distance from the attentional focus when the task is more demanding of processing resources. For example, the gradient has been shown to be steeper when a more difficult orientation or form discrimination had to be made, compared to an easier luminance or brightness discrimination, and when targets are closer together (Downing, 1988).

One of the most recent findings regarding the attentional distribution shows that a belt of perceptual suppression can surround the center of the attentional focus, within which processing is enhanced. Beyond the region of suppression, the benefit of attention is weaker than that observed in the center of the attentional focus. This benefit subsequently degrades to an asymptote (Cutzu & Tsotsos, 2003). This type of distribution has been termed a "suppressive annulus" (Cutzu & Tsotsos, 2003) and "Mexican hat," due to its graphical similarity to a sombrero (see Figure 1). This observation of the attentional distribution is considered reliable in that it has been demonstrated when controlling for variables that may allow for explanations of this shape other than it being a function of the distribution of VA (Müller, Mollenhauer, Rösler, & Kleinschmidt, 2005). This observation represents a change from the previous three in that it does not share the view that attention decreases in a linear manner with increasing distance from the center of attentional focus. Thus, it is the only theory that is able to account for studies identifying regions of suppression. The suppressive annulus observation is also useful in that it allows for making dynamic predictions concerning the effects of background information. The existence of a focus of attention surrounded by a suppressive annulus would suggest that background information, should it be useful, can also provide benefit when located in the area of suppression, and that distracting information is unlikely to interfere with processing when it is located in this region.

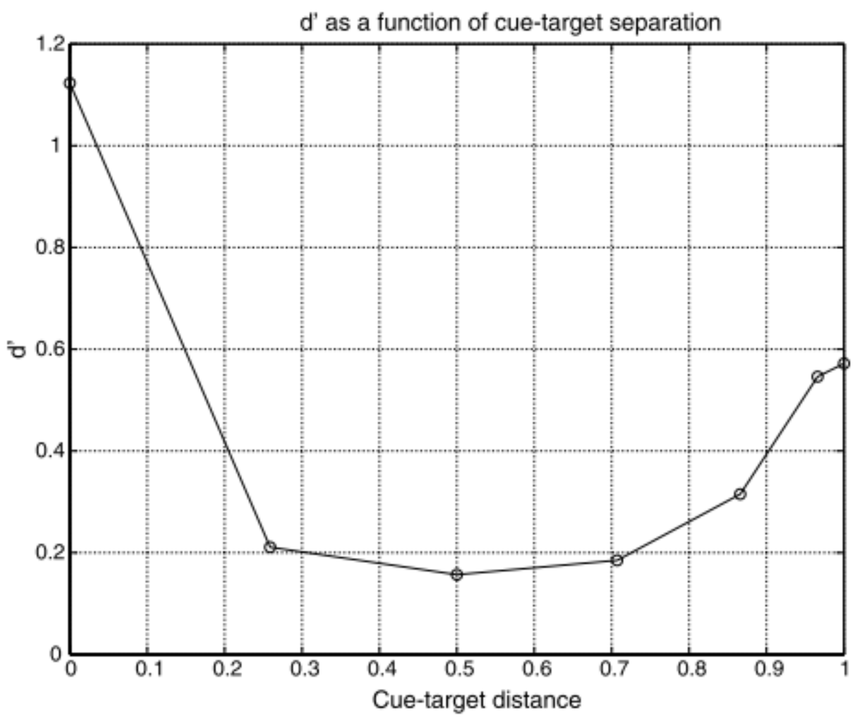


Figure 1. Graph of one half of the Mexican-hat distribution (Cutzu & Tsotsos, 2003)

Behavioral evidence suggests that the Mexican hat observation is the most accurate with regards to ability to account for the observation that the processing of ground information can lead to enhanced performance. The optimal size of a pre-cue for visual search is close to target size (Greenwood & Parasuraman, 1999, 2004), but the optimal size of a pre-cue for WM tasks appears to include both figure and a small amount of ground (Greenwood, Lambert, *et al.*, 2005). The latter finding suggests that it may be important to represent both figure and ground in order to maintain a strong mental representation of an object. Additionally, it has been shown that there are unique firing patterns to both figure and ground stimuli, with enhanced neuronal firing to the figure and suppressed firing to the ground when no target was visible (Super, *et al.*, 2001). The only shape of the attentional distribution that is consistent with these findings is the Mexican hat. The Mexican hat distribution predicts that a benefit from non-conflicting background information can be obtained when the information is located slightly away from the center of attentional focus and a suppression of stimuli located just outside the area of attentional focus. However, the presence of background information is not always beneficial, such as when the stimuli do not need to be remembered later, but acted on immediately, as in the case when performing a selective attention task during a WM task. In such cases, the presence of background, especially when the information in the background is potentially conflicting in nature to the attentional task at hand, is associated with a decline in performance as evidenced by both behavioral and neurological data (de Fockert, Rees, Frith, & Lavie, 2001). However, we speculated that the Mexican hat theory may suggest that if the distracting information is located further away from the focus of attention—along the "brim" —it may not influence processing.

Given its ability to account for findings of regions of suppression and effects of background information, the suppressive annulus view is assumed in this dissertation to be the most accurate representation of the attentional distribution. Regardless, it appears as though the shape of the attentional distribution may vary depending upon task requirements. Given that the integrated view suggests shared processing resources between WM and VA, such that taxing WM resources should cause graded alterations in the properties of VA, such as the attentional distribution. Thus, it was predicted that the manipulation of WM load would result in not only a change in the processing efficiency in the center of the attentional focus but also a change in the shape of the attentional distribution.

Working Memory (WM)

WM is defined as the storage and manipulation of relevant information so that it is available for use in the immediate future (Baddeley, 2007; Cowan, 1999), particularly when a goal-oriented action is required. One of the most critical, and debated, components of WM is its capacity. The capacity of WM is often the limiting factor in efficient operating ability and, given the substantial amount of tasks requiring WM, plays a crucial role in many cognitive tasks (Baddeley, 2007; Cowan, 1999).

WORKING MEMORY CAPACITY (WMC)

Most theorists agree that there is some limit to the amount of information that can be stored in WM—a working memory capacity (WMC). Recently it has been demonstrated that WMC is about four chunks of information (Cowan, 2001). The cognitive process of "chunking" occurs when certain items are grouped together to form an object. It appears as though regardless of the number of features that are integrated, approximately four objects can be held in WM at any given time (Cowan, 2001). Thus, chunking allows for the storage of more information in WM.

While there is a general consensus that WMC is approximately four chunks, it has also been demonstrated that there is a certain degree of individual variation in WMC. A previous study indicates that this variation is the result of the efficiency with which individuals allow items access to WM (Vogel, McCollough, & Machizawa, 2005), such that individuals with low WMC are more likely to process distracting information. Based on that data, Vogel argued that the neurophysiological basis underlying the observation of inter-individual differences in WMC capacity that is explicitly related to the ability to exclude irrelevant information from WM. Given that the ability to enhance pertinent information is typically attributed to VA, this phenomenon also suggests a close relationship between WM and VA. Further, it has been shown behaviorally that inter-individual differences in WMC are associated with differing apportions of attention. Specifically, low-WMC individuals allocated attention as a spotlight, while high-WMC individuals demonstrated flexible attentional allocation (Bleckley, Durso, Crutchfield, Engle, and Khanna, 2003).

General Relationship between WM and VA

While WM and VA can function independently, they can appear to be related. Although there is a substantial amount of evidence suggesting that these two processes are capable of interacting, the extent of this relationship is not well understood. We hypothesized that when WM and VA are simultaneously deployed, an integrated cognitive process is formed.

The existence of a relationship between WM and VA is well supported, particularly in studies examining WMC. As was detailed in the previous section, WMC is thought to be four chunks of information, where a chunk represents the particular level of feature integration (Luck & Vogel, 1997). This suggests that the "level" at which VA operates (i.e., whether stimuli are viewed as integrated objects or as individual features) is a key component to WMC. Attention has also been associated with the large degree of individual variability in WMC, such that high-WMC individuals are more efficient at excluding distracting information (Engle, 2002; Vogel, *et al.*, 2005), a function that may be associated with VA (Bleckley, *et al.*, 2003).

There is evidence that supports the plausibility of WM and VA combining to form an integrated process in that they appear to have a reciprocal relationship. As an example of VA's ability to affect WM, it has been shown that the engagement of the attentional system enhances performance in WM tasks (Awh, Jonides, & Reuter-Lorenz, 1998). Additionally, not only is memory for spatial targets enhanced at memorized—as compared to non-memorized—locations, but the diversion of attention away from the location held in WM leads to a decreased ability to remember those locations (Awh, *et al.*, 1998). This suggests that WM and VA are not merely related, but that spatial attention is necessary for efficient working memory processing. One of the mechanisms through which VA is able to influence WM may be its relationship with WMC, the specifics of which are discussed above. WM is also capable of manipulating VA. For example, the active maintenance of an object in WM has been shown to shift attention to that object, if seen again, even when there is no impetus to direct attention to the object (Downing, 2000). While the existence of a reciprocal relationship between WM and VA suggests that the two processes have the potential to become fully integrated it does not provide evidence of the formation of a new process.

While there is a large amount of evidence suggesting that WM and VA are capable of influencing each other, the details of this interaction are not well understood. The degree of complexity involved in this interaction is well illustrated through the comparison of studies conducted by Downing and Dodds (2004), Woodman and Luck (2002), and Oh and Kim (2003). These studies were all aimed at exploring the hypothesis that attentional capture (i.e., the ability of external objects similar to those stored in WM to capture VA) is an obligatory phenomenon. While the studies by Downing and Dodds (2004) and Woodman and Luck (2002) both failed to find support for this hypothesis, Oh and Kim (2003) provide evidence that explain these negative results. Oh and Kim (2003) suggest that the results of the aforementioned studies are likely attributable to their design, as opposed to the desired experimental effects of attentional capture. Oh and Kim (2003) demonstrated that the paradigms used in the Downing and Dodds (2004) and Woodman and Luck (2002) studies introduced the potential for competitive interaction between the task utilized to guide VA and the object held in WM. Specifically, the task to guide VA and the object held in WM were cognitively similar. This competition for resources eliminated potential attentional capture effects by the object in WM. As another example of the complexity of the relationship between WM and VA, when WM load is increased, visual search efficiency decreases, but only if the target template for the visual search is changed trial to trial, as opposed to held constant throughout the study (Woodman, 2003). Together, these results not only suggest that VA and the WM share at least some of the same resources, but also highlight the importance of understanding the intricate and sensitive relationship between WM and VA.

While behavioral data provide strong support of a relationship between WM and VA, neurophysiological measurements provide greater insight into the mechanics of this relationship. For example, an fMRI study showed that while there is considerable overlap in the areas activated by tasks involving either WM or VA, there also exist areas that are uniquely activated by each process alone (LaBar & Gitelman, 1999). Additionally, an attention-sensitive ERP component has been localized to the striate cortex and is the result of feedback from posterior areas (Martinez, *et al.*, 1999; Noesselt, *et al.*, 2002), which are areas where WM storage occurs (Supèr, Spekreijse, & Lamme, 2001; Todd & Marois, 2004). Similarly, the activity from the extrastriate neural generators of the ERP component P1, which also have been associated with WM storage (Todd & Marois; others), was modulated by attentional pre-cues (Luo, Greenwood, &

Parasuraman, 2001). These ERP studies suggest at least an interactive relationship between VA and WM storage. Recent ERP studies provide evidence suggesting that the relationship between attention and WM may go beyond one of simple interaction and instead form an integrated process when required in the same task. In these studies, waveforms over the posterior scalp contralateral to the to-be-remembered stimulus that are recorded 300-900ms after delay period onset are used to create a difference waveform (Ruchkin, *et al.,* 1997; Klaver, et *al.*, 1999). Specifically, the voltage at ipsilateral electrodes is subtracted from the voltage at contralateral electrodes to create a difference waveform; this data is then averaged between 300-900ms after delay period onset to create what is termed the contralateral delay activity (CDA; e.g., Vogel, *et al.*, 2004). The CDA has been shown to be differentially modulated depending on whether VA and/or WM are manipulated (Vogel & Machizawa, 2004; Clarke, *et al.*, 2010). Although behavioral and physiological evidence supports a close relationship between WM and VA, it is currently unclear whether or not they become a fully integrated process when the two are simultaneously deployed. This evidence suggests that the WM and VA have a reciprocal relationship both behaviorally and physiologically, implying that the simultaneous deployment of WM and VA is an ideal scenario for the formation of a new process.

Models of WM and Attention

Several theories have been advanced to explain the array of findings concerning the relationship between WM and attention in a meaningful way, where the definition of attention expands beyond that of VA to also include non-visual stimuli. The best-known of these theories are the specialization (reviewed in Baddeley, 2007) and embedded processes (Cowan, 1999) models. These models are largely considered competing, but may also be complimentary in some respects. While both types of models assign an important role for attention in the WM process, neither makes predictions concerning whether they become fully integrated or operate in parallel when simultaneously deployed.

Among the first theories of WM and attention to gain a large degree of traction in the scientific community were those theories included specialized sub-systems. One of the most prominent of such models is Baddeley's multicomponent processing model (reviewed in Baddeley, 2007; see Figure 2). This model, at its most basic, consists of two components: the central executive and specialized sub-systems. There are multiple specialized sub-systems: the visuospatial sketchpad, phonological loop, and episodic buffer. The visuospatial sketchpad and phonological loop can be further broken down into even more specialized components—visual cache, and the inner scribe, phonological store, and articulatory loop (reviewed in Baddeley, 2007).

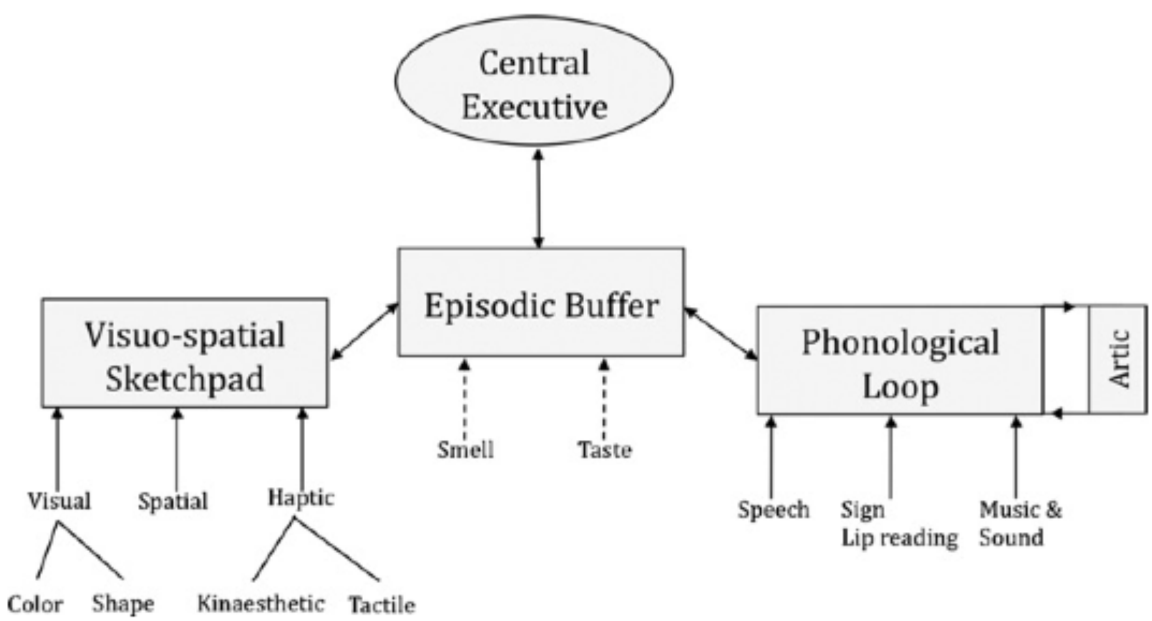


Figure 2. Graphical depiction of the multicomponent model

The defining characteristic of the multi-component model is that each portion of this model is attributed unique responsibilities. The central executive is responsible for binding pieces of information together to form a coherent event/episode and to coordinate the sub-systems. Important to this dissertation, this model considers the central executive as the seat of attention and inhibition. The three sub-systems all perform separate specialized functions of WM. The phonological loop is responsible for the storage of auditory information and the transformation of visually presented information into auditory information. This component can be further subdivided into the phonological store and the articulatory loop. The phonological store houses auditory information that is vulnerable to rapid decay, while the articulatory loop retrieves relevant auditory memory traces. The visuospatial sketchpad can be further subdivided into the visual cache, which stores information regarding form and color, and the inner scribe, which handles spatial and movement information, as well as serving as the rehearsal area for information in the visual cache (as reviewed in Logie, 2011). The final sub-system, the episodic buffer, is the latest addition to the multicomponent theory. This system is tasked with the integration of stimuli across sensory domains with time, in order to form an accurate event memory.

Support for the multicomponent model is derived from studies that demonstrate that a deficit in one of the sub-systems does not necessarily lead to deficits in domains supported by other portions of the model, or in general cognitive ability. These effects are demonstrated either through the use of patient populations, or by inducing deficits in specific domains by imposing demands on a specific domain that exceed its capacity. For example, an interference paradigm has been used to demonstrate that visual span is impaired by an interpolated visual task, but not by a spatial task (Della Sala, Gray, Baddeley, Allamano, and Wilson, 1999). This suggests that talking and short-term verbal memory share cognitive resources that are different than those utilized for temporary storage of a visual pattern.

Further support for the multicomponent model can be found in certain electrophysiological findings. For example, it has been shown that the N2pc, an electrophysiological component related to distractor suppression, changes in polarity and timing dependent upon whether the participant is searching for an object in a perceived display or an object held in WM, (Astle, *et al.*, 2009). It was argued that the search within WM elicited a later positive waveform because the features of the objects had become bound, requiring an additional cognitive step–feature separation, when compared to searching a perceived display. This finding can be explained by the multicomponent theory of WM, which holds that the episodic buffer houses integrated objects, while the temporary stores are responsible for the storage of feature information (as reviewed in Baddeley, 2007). If this theory were correct, it would suggest that the reason for the opposing polarities observed by Astle, *et al.* (2009) is that the information is being stored in different areas within WM. This would be manifested as the early temporary storage of mental representations by their features, such as the visual cache, which is later followed by integration of these features into objects and their subsequent transition to storage within the episodic buffer. However, previous literature has shown that the visual cache is also capable of storing "bound" visual objects (Logie, 2011). An extension of the multicomponent model that delineates when objects are stored in the episodic buffer versus the visual cache is necessary to allow the theory to appropriately account for the aforementioned findings.

While there is evidence to support the specialized sub-systems claimed for the multicomponent model, there is also evidence that is not consistent with the model. The primary complaint concerning that model is that it does not support the recent evidence that WM is an emergent property. Previous WM literature is taken to suggest that WM is the result of the coordination by attention of brain systems responsible for various aspects of WM (Postle, 2006). Instead, the model views WM as composed of individually operating sub-systems. Postle (2006) has argued that WM is an emergent property and not the result of specialized sub-systems for a few substantial reasons. First, the view of WM as composed of specialized sub-systems necessitates an extraneous number of such sub-systems to account for all of the literature. Further, the number of specialized brain regions and networks that would be necessary to support all of these sub-systems is not feasible due to anatomical constraints (Postle, 2006). Finally, while there is some evidence to support the existence of specialized subsystems, Postle (2006) argued that the results of these studies are generally an artifact of poor methodology. Supporters of the multicomponent theory counter these criticisms by stating that it is a theoretical model and the specialized sub-components are not intended to represent specialized brain areas (Logie, 2011). An additional shortcoming of the model is that, while it carves out a role for attention within WM, it fails to make predictions regarding the nature of the relationship between these two processes. This complaint has been largely unaddressed.

Cowan's embedded processes model is an alternative theory of the relationship between WM and attention. This model is able to account for the aforementioned emergent property criticism (Postle, 2006) that plagues the multicomponent theory (Cowan, 1999; see Figure 3). The embedded processes model achieves this by suggesting that WM is a continuous stream of processing controlled by a central executive. The processing stream begins with the admittance of all stimuli to a brief sensory store. These stimuli are then received into either the long- or short-term store, where the short-term store is simply the activated portion of the long-term store. When stimuli are in activated memory, the central executive works to direct the focus of attention to novel stimuli and/or unchanged stimuli that are deemed important. Once within the focus of attention, the central executive then determines the appropriate controlled action(s). Stimuli that are in short term store but not the focus of attention can also result in action, but only if the actions are automatic in nature. Thus, in this model, VA acts on WM by controlling the stimuli that the individually may respond to in ways other than those afforded by subconscious/automatic processes.

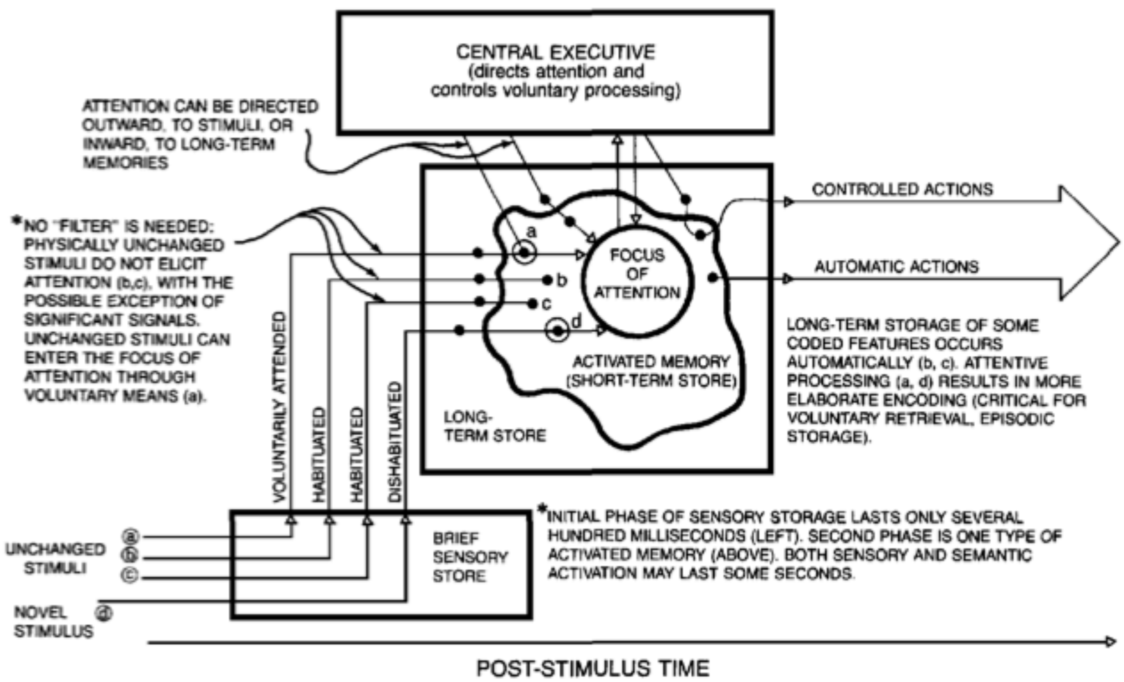


Figure 3. Graphical depiction of the embedded processes model (Cowen, 1999)

In contrast to the multicomponent model, Cowan's embedded processes model does not view WM as the product of numerous domain specific sub-systems but rather as a method by which attention may be focused on activated contents of short-term memory storage. This gives rise to an additional difference between embedded processes and the multicomponent models. In the embedded processes model, the capacity of WM is limited but flexible, in that it is not specific to any processing domain, with capacity around four chunks, while in the multicomponent view, WMC is the result of the capacity limit of the domain specific stores involved in the processing. Interestingly, in the multicomponent view the episodic buffer has the same capacity restraints as the embedded process model (Baddeley, 2011). A further difference is that the embedded processes model places a large degree of importance on attention, which is assigned responsibility for the efficiency of WM processing—including activation and maintenance of mental representations, attention switching, inhibition, and suppression of unnecessary response tendencies. The multi-component view places less emphasis on attention in that it is only responsible for the coordination of subsystems and the integration of information.

While there are many differences between the multicomponent and embedded process models, it has been suggested by Logie (2011) that they are not necessarily opposing viewpoints, but instead are complementary theories that differ in their research question. Logie (2011) has argued that the embedded process model is concerned with the manner in which the limited-but-flexible capacity limit of WM affects performance, while the multicomponent theory is concerned with what contributes to this capacity limit. This difference renders the models complementary in that they are designed around different experimental questions. Specifically, the embedded processes is well suited for asking questions concerning the individual differences in WM, while the multi-component theory is suited for revealing the functional organization that supports WM performance.

Other current relevant models of WM and attention, the executive attention theory of WMC (Kane, Conway, & Hambrick, 2007) and the dual mechanisms of control model (DMC; Braver, Paxton, & Locke, 2009), respectively, are very similar to each other and to the embedded processes model. The primary difference between the embedded processes model and the executive attention theory of WMC involves the nature of WMC. The executive attention theory of WMC argues that since WM span can predict performance on an anti-saccade test, there is a link between WMC and controlled attention (Kane & Bleckley, 2001), suggesting that differences in WMC are due to the efficiency with which storage is utilized. In contrast, in the embedded processes model, WMC limits are based primarily on available space. The executive attention theory of WMC and the DMC also differ regarding WMC. Specifically, the DMC suggests that inhibition drives WMC, while the executive attention theory of WMC states that there is an attention-control capability that underlies and drives both WMC and inhibition.

While a number of models of WM have been proposed, none of them make specific and testable predictions regarding the nature of the relationship between WM and VA when they are simultaneously deployed. Thus, the nature of the relationship between WM and VA that is reported in this dissertation will result in the necessary amendment of existing models of WM to account for the findings.

Contralateral Delay Activity/Sustained Posterior Contralateral Negativity (CDA/SPCN)

A useful approach for studying the interaction between WM and VA capitalizes on activity related to WM maintenance recorded from the scalp during the retention period of a delayed match-to-sample task (Klaver, *et al.*, 1999; Ruchkin, *et al.*, 1997). Specifically, this sustained activity that is observed over the posterior scalp contralateral to the to-be-remembered stimulus (Ruchkin, *et al.,* 1997; Klaver, et *al.*, 1999). The activity that is relevant to WM maintenance can be isolated from noise by subtracting the voltage at ipsilateral electrodes from the voltage at contralateral electrodes to create a difference waveform (Klaver, *et al.*, 1999). There have been a few proposed names for this activity, notably: the contralateral delay activity (CDA) (McCollough, *et al.*, 2007; Vogel & Machizawa, 2004) and the sustained posterior contralateral negativity (SPCN; Dell'Acqua & Sessa, 2006). Previous work has shown that this difference wave becomes more negative in polarity when WM load is increased. Our work showed that the difference waveform became more positive when VA was constricted and less negative when VA was constricted when both WM and VA were manipulated. However, when both VA and WM were manipulated there was only an effect of increased constriction of VA when WM load was high. Given that the polarity of this waveform is dependent upon the cognitive process being manipulated, this dissertation uses the term CDA rather than SPCN.

The posterior-lateral brain regions where the CDA is observed had been previously associated with the processes of WM per se. Specifically, single unit studies have shown that, in monkeys, in area V1 there is enhanced firing to the figure and suppressed firing to the ground of a figure-ground stimulus (Supèr, *et al.*, 2001). Similarly, in humans, the BOLD signal originating from the posterior parietal cortex was correlated with WM capacity (Todd & Marois, 2004). However, it should be noted that, in humans, other types of physiological measurements have revealed a bilateral and/or contralateral-only response to a unilateral stimulus presentation, suggesting that the CDA is not the result of an isolated process (Robitaille, *et al.*, 2010). There is also evidence that processes related to VA occur in similar brain regions. For example, it has been shown that the N2pc, which is located over the visual cortex contralateral to an attended stimulus, is modulated according to whether VA is directed to a perceived or remembered stimulus (Astle, *et al.*, 2009).

While previous literature suggested that posterior parietal areas were involved various aspects of WM, the CDA itself has been associated with WM load (McCollough, *et al.*, 2007; Vogel & Machizawa, 2004) and WM capacity (Vogel, *et al.*, 2005). The association between the CDA and WM load comes from observations that the amplitude of the CDA becomes increasingly negative with increased WM load and reaches an asymptote at four chunks (McCollough, *et al.*, 2007; Vogel & Machizawa, 2004). This finding was shown not to be an artifact of the amount of space occupied by the increased number of stimuli (McCollough, *et al.*, 2007). Given that WMC is thought to be typically four chunks, this finding suggests that not only is the CDA likely to index WM load, but that it also has a relationship with WMC. Further exploration into the relationship between the CDA and WMC has shown that an individual's WMC is strongly correlated with an increase in CDA amplitude from two to four chunks, but not with CDA amplitude increase between four and six chunks or with the absolute amplitude for any array size (Vogel & Machizawa, 2004). Additionally, high and low-WMC individuals show different patterns of filtering efficiency, an index derived from CDA amplitude, with individuals with low-WMC less able to ignore distracting information (Vogel, *et al.*, 2005). Together these studies provide strong evidence for the ability of CDA amplitude to index WM load and measure WMC.

The CDA has also been associated with VA. We observed that the presence of a pre-cue to target location–regardless of size--produced a CDA over posterior cortex that was positive in polarity, and, moreover, the positivity increased with cue precision. The analysis of the underlying hemispheric components of this effect reveals that the positive polarity is due to the ipsilateral activity being more negative than the contralateral activity. Thus, when the ipsilateral voltage was subtracted from the contralateral voltage, the resulting difference waveform was positive in polarity. Follow up studies suggest that these findings were not a function of the slightly different paradigm used in this study compared to the earlier studies examining effects of WM on the CDA (Clarke, *et al.*, 2010).

We also examined the effect on the CDA of manipulation of both WM and VA within the same task. We found that there was an effect of manipulation of VA, such that the CDA amplitude became less negative in pre-cue conditions, regardless of WM load. However, when WM load was low there was no effect of increased attentional constriction while when WM load was high the CDA amplitude became less negative with increased attentional constriction (Clarke, *et al.*, 2010). These results provide further evidence that the CDA is an appropriate measure for studying the relationship between WM and VA.

We have also shown that not only is the CDA modulated by VA, but also so are difference waves based on data from frontal areas. Specifically, when difference waves were calculated from frontal scalp sites, the effects of attention held: the positivity of the amplitude of the frontal difference waveforms increased when VA was manipulated. This is not surprising considering that there is evidence for the existence of a relationship between the PFC and the parietal areas regarding the cognitive process of attention via the dorsal attention network (Corbetta & Shulman, 2002; Goldman-Rakic, 1996). Previous work has demonstrated the existence of three prefrontal-dependent mechanisms involved in the regulation of attentional control (Yago, *et al.*, 2004). However, given that the effects of these mechanisms are observed between 150-350ms (Yago, *et al.*, 2004), and that CDA effects are observed between 300ms and 900ms, it is unlikely that any of these mechanisms are responsible for any CDA related results. Instead it is suggested that the positive CDA observed when VA is manipulated is the result of the activation of the dorsal attention network (Corbetta, et al., 2008) by attentional cues.

The finding that the polarity of the CDA varies according to whether VA and/or WM were manipulated is supported by other ERP literature. Specifically, manipulations in WM and VA have also been associated with physiological changes in the N2pc ERP component. The N2pc is considered to be a correlate of distractor suppression that is related to attentional selection (Luck & Hillyard, 1994) and is topographically similar to the delay period activity (i.e., CDA) that follows it (Brisson & Jolicœur, 2007; Jolicœur, Brisson, & Robitaille, 2008; McCollough, *et al.*, 2007; Perron, *et al.*, 2009; Robitaille & Jolicœur, 2006; Robitaille, Jolicœur, Dell'Acqua, & Sessa, 2007). Imaging data indicates that the N2pc is generated parietally and is seen in ERP's over the posterior cortex contralateral to an attended stimulus (Astle, *et al.*, 2009; Hopf, *et al.*, 2000). While similar, the N2pc and the CDA have been shown to be separate components, in that they have different time courses (Jolicœur, Brisson, & Robitaille, 2009) and the CDA is observed in tasks that manipulate attention as well as WM (Clarke, *et al.*, 2010). Astle and colleagues (2009) showed that the polarity of the N2pc was reversed depending upon whether a feature search task occurred on a perceived array or on one held in WM. When searching the perceived array, the N2pc is negative over the region contralateral to the target and positive contralateral to the distractor, with the opposite pattern being true when searching the array in WM. The authors suggest that this can be attributed to features becoming bound into objects once they enter WM since searching a remembered array necessitates an extra step—feature extraction. This suggests that the observed contralateral N2pc negativity is an index of enhancement and the contralateral N2pc positivity of suppression at a spatial location (Astle, *et al.*, 2009) and provides credence to the Clarke, *et al.* (2010) finding that the polarity of the CDA is dependent upon whether attention and/or WM is manipulated. Thus, the literature suggests that the CDA is an appropriate measurement tool when examining the nature of the relationship between WM and VA.

Summary of Previous Findings

The processes of WM and VA are vital to the successful completion of many tasks. Although WM and VA can be considered separately, they are also inherently related processes. While there is a great deal of evidence supporting a relationship between WM and VA, the exact nature of this relationship remains unknown.

VA has been shown to lead to enhanced processing of a target and may also be associated with the suppression of distracting information (Super, *et al.*, 2001). The timing and distribution of attention are critical properties of its ability to affect processing. Current evidence suggests that VA is capable of acting at a multitude of points in the processing stream (e.g., Griffin & Nobre, 2003). It has been demonstrated that the deployment of VA prior to or following target presentation leads to similar behavioral results, in that performance is enhanced (Griffin & Nobre, 2003). However, physiological evidence from the same study suggests that the timing of attentional deployment may result in different underlying processes. The attentional distribution in space is another inherent property of the process of VA. There are many observed shapes of the attentional distribution, which we suggest are the result of differing task demands.

WM is commonly defined as the process by which relevant information is made available for immediate use. A critical and limiting factor of WM processing efficiency is WMC. It is widely accepted that WMC is approximately four chunks, with some degree of individual variation (Cowan, 2001). This individual variation may be the result of filtering efficiency. One study demonstrating that low-WMC individuals are less efficient at filtering out distracting information than high-WMC individuals (Vogel, *et al.*, 2005) while another showed that differences in WMC were the result of whether VA was distributed strictly as a focused spotlight (low-WMC) or whether the distribution of VA was more flexible (high-WMC; Bleckley, *et al.*, 2003).

Behavioral and physiological evidence supports the view that VA and WM are separate processes that interact. This has been demonstrated both behaviorally and physiologically (e.g., Awh, *et al.*, 1998; Clarke, 2010; Downing, 2000; Engle, 2002; Vogel, *et al.*, 2005; LaBar & Gitelman, 1999; Greenwood, Fossella, & Parasuraman, 2005; Greenwood, Lin, Sundararajan, Fryxell, & Parasuraman, 2009; Parasuraman, Greenwood, Kumar, & Fossella, 2005). The support of a relationship between WM and VA using a variety of measurement techniques provides strong evidence in favor of WM and VA being separate processes that have the potential to combine and form a new process when simultaneously deployed.

There are a number of different models of WM, most of which assign a role to attention. The best-known of these theories are the multicomponent model (as reviewed in Baddeley, 2007) and the embedded process model (Cowan, 1999). While both theories identify attention as an executive decision maker the multicomponent model attributes less responsibility to attention and has a capacity limit based on the activated sub-systems. In the embedded processes model attention plays a larger role, and WMC is held constant regardless of the type of information being processed (as reviewed in Baddeley, 2007; Logie, 2011; Cowan, 1999). It has been suggested that these two models are not opposing viewpoints, and instead are complementary paradigms aimed at measuring different types of research questions. Neither model makes explicit predictions regarding the exact nature of the relationship between WM and VA.

Difference waves calculated from EEG activity recorded during the delay period of a task are an important way to examine different aspects of the relationship between WM and VA. When the ipsilateral waveforms are subtracted from the contralateral waveforms from posterior scalp, a difference wave is formed, termed the CDA. This activity is sensitive to both WM (McCollough, *et al.*, 2007; Vogel & Machizawa, 2004) and VA (Clarke, *et al.*, 2010). Interestingly, the polarity of the CDA is dependent on whether WM, VA, or both WM and VA are manipulated (Clarke, *et al.*, 2010; McCollough, *et al.*, 2007; Vogel & Machizawa, 2004). This suggests that WM and VA are related, and that their interaction can be probed through the manipulation of the CDA.

Rationale

The goal of this dissertation was to test the hypothesis that when simultaneously deployed, WM and VA form an integrated process or interact at various points, but operate in parallel. This dissertation focused on the effects of taxing the resources of one process on properties of the other, with these properties being the effect of the timing of the deployment of VA in the processing stream, the attentional distribution, and filtering efficiency. This is the first testable hypothesis of the nature of the relation between VA and WM. In addition to behavioral measures a neurophysiological methodology, CDA, was also used to test this hypothesis. The results of the current study may allow for additional specificity in the models of WM and improve the development of tasks that require both WM and VA. It was hypothesized that the results would support the integrated view of WM and VA—that when WM and VA are in concurrent use a new process is formed—rather than the parallel view—that WM and VA interact but do not become fully integrated when simultaneously deployed.

Experiment 1 was designed to test one prediction from the integrated model that a new process formed through the integration of WM and VA would operate on the shared resources normally associated with each individual process. These resources should include those attributed to WM processing (i.e. storage and manipulation of relevant information) as well as those allocated to properties of WM and VA (i.e., WMC and the properties of the attentional distribution). We tested this by manipulating the timing of cue-driven attentional manipulation during WM encoding and maintenance, specifically pre- and post-cues. Although the few previous studies that looked at effects of both pre- and post-cues during a WM task found effects of pre-cues were similar to post-cues (Griffin and Nobre, 2003), those studies did not use demanding tasks. We reasoned that use of easy tasks would not load the shared resources, as neither WM nor VA resources would be taxed in that scenario. The integrated view predicted that the formation of one integrated process—rather than two interacting processes—allows for the sharing of processing resources between WM and VA. If so, VA should be able to exert effects on all stages of processing following its deployment. Thus, post-cues can only operate during maintenance, while pre-cues, which are presented before the stimuli, can alter both encoding and maintenance. The ability of pre-cues to operate on more stages of processing than post-cues allows pre-cues to have a stronger effect on formation and maintenance of the mental representation. This additional portion of the WM processing stream that is affected by pre-cues may not result in observable behavioral effects when WM processing demands are low, and the requirements for efficient processing are easily met, but is likely to produce differences when WM demands are increased resulting in a tax on WM resources. The integrated view predicts that pre- and post-cues would result in similar behavioral effects when WM load was low, but when WM load was high, post-cues would be associated with less efficient processing compared to pre-cues. The parallel model predicts that since the two processes interact, but a new process is not formed, then resources would not be shared between WM and VA. Consequently, VA could only act on the discrete stage of processing during which it was deployed such that pre-cues would affect encoding while post-cues would affect maintenance. The parallel view therefore argues that WM task performance would not be altered as a function of the timing of VA deployment, regardless of WM load.

Experiment 2 was designed to test one prediction from the integrated model—that increased WM load should influence the shape of the distribution of VA. Given that processing resources are shared in the speculative new process, any alteration in the resources of WM or VA should result in graded changes in the resources allocated to the properties of the other. This prediction was tested by examining whether or not the distribution of VA was modified in response to WM manipulations. If the integrated model were correct, then processing resources would be shared between WM and VA, resulting in a narrower, but stronger range of optimal attentional focus and suppressive annulus. This prediction was based on the results from an earlier study demonstrating that increased WM load decreased distractor interference, suggesting that VA becomes more focused during high load conditions (Chen & Chan, 2007). If WM and VA are parallel processes, then they would not share processing resources and thus, when WM load was manipulated, the distribution would be affected by the increase in task difficulty, resulting in a general change in the effect of VA but no difference in the *shape* of the attentional distribution.

Experiment 3 was designed to test the prediction that manipulating attentional constriction would lead to changes in the relationship between WMC and the ability to exclude distracting information from WM processing. This prediction is derived from the fact that an integrated process would operate on the shared resources typically allocated to WM and VA individually. This experiment examines whether manipulating attentional resources results in graded changes in WM processing. Specifically, the third experiment explored the effect of attentional constriction on the filtering efficiency of high- and low-WMC individuals. Previous work reported that low-WMC individuals allow more irrelevant stimuli to enter WM during maintenance than high-WMC individuals (Vogel, *et al.*, 2005). This finding was interpreted as suggesting that those with low-WMC were less able to filter out distracting information. Thus, it was hypothesized that use of VA reduces the amount of distracting information that must be processed and consequently may alter the relationship between filtering efficiency and WMC. If the integrated model is correct, then, given that WM and VA would share processing resources, changes in one process should lead to graded changes in the other– the relationship between filtering efficiency and WMC would change with increased VA constriction. It was predicted that increased constriction of VA would result in increased similarity in the filtering efficiency of low- and high-WMC individuals. If the parallel model is correct, then attentional constriction would result in increased similarity in the filtering efficiency of low- and high-WMC individuals, but this similarity would not be modulated by increased attentional constriction.

2. EXPERIMENT 1

Background

The integrated view hypothesized that when WM and VA are deployed simultaneously they form an integrated process. If so, then effects of VA on WM would not be exerted only on one stage in the processing stream (the stage active when VA was manipulated), but rather would carry over to later processing stages. We further predicted that carryover effects of VA would be stronger under greater WM load. If the integrated view is correct, then the new process should share the cognitive processing resources normally allocated to WM and VA individually. Thus, when WM resources are taxed, the benefits of VA on target processing would be heightened. Following the same logic, the presentation of both a pre- and post-cue would heighten target processing compared to presentation of a post-cue only.

The parallel view, by contrast, predicts that pre-cues and post-cues should only exert effects on the stage of the WM processing during which they appear. Additionally, in the parallel view, WM and VA do not share attentional resources. This suggests that the change in WM resource demand created by a manipulation of WM load would not interact with cuing effects. According to the parallel view, each cue acts on only one stage of processing and cannot build upon the benefits provided by a previous cue. Therefore, when presented within the same trial, the pre-cue would influence target encoding and the post-cue would influence maintenance of target mental representation. Thus, by this parallel view, the post-cue could either direct attention to the target, or disrupt the processing of the target begun by the pre-cue.

The results provide evidence to support the view that WM and VA form an integrated process when simultaneously deployed. Additionally, this experiment demonstrates other results commonly found in the literature. Specifically, we found that pre- and post-cues resulted in similar WM performance (Griffin & Nobre, 2003), but only when WM resources were not taxed under low load. WM performance was enhanced by increased cue precision. WM performance suffered when WM load was increased.

Methods

PARTICIPANTS

This study was conducted on 29 participants (10 male) between the ages of 18 and 27 (average = 20.79 years). Participants were all George Mason University students who received course credit in exchange for participation. All participants gave informed consent following procedures approved by George Mason University's internal review board (IRB).

MATERIALS

Participants performed a computer-based task that was implemented in E-Prime. All behavioral data was collected using E-Prime and a keypad.

STIMULUS DISPLAY

This experiment was designed to explore the relationship between WM load and the timing of cue-driven attentional deployment. This required the manipulation of all three factors in a crossed paradigm. There were three levels of Cue Condition: no-cue, small cue (diameter = 2.6°), and large cue (diameter = 3.6°). There were two levels of

WM Load: four items (high) and two items (low). The timing of attentional deployment was also manipulated. There were three levels of Timing: cue deployed pre-stimulus presentation (pre-cue), cue deployed post-stimulus presentation (post-cue), and cues deployed both pre- and post-stimulus presentation (both-cues). Cue sizes were selected on the basis of previous work exploring the relationship between WM and VA (CDA Experiment 2b). Cues were L-brackets that formed only the corners of a square (see Figure 4). The target (1x1° arrays of 7 randomly oriented lines) was always presented in the center of the cue. Participants were seated with their eyes 60cm from the screen. The trial conditions were presented in a random order. Location of targets and cues were randomized with the constraint that they never overlapped with the central fixation cross. Targets were always presented within the same location previously occupied by the cue. All target arrays and cues were presented on a gray background. Arrays were blue, green, red, yellow, black, white, or violet on a gray screen, and the test array was always in the same location as the target array. On trials when a test array differed from the target array, only one of the stimuli was different.

Each trial consisted of seven events which varied depending on condition. All trials began with the presentation of a fixation cross for 100ms, which remained visible throughout the trial. The timing of subsequent events depended on condition (see Figure 4).

Under pre-cue only, the fixation cross was followed by the onset of a cue, lasting 100ms. This was followed by onset of the target array, lasting for 150ms. After target array offset, a screen showing only the fixation cross was displayed for 1300ms. Participants were asked to retain a memory of the target array during this interval. Finally, the comparison screen appeared, consisting of a target array. Participants were directed to press one of two keys to indicate whether the comparison target array was the same or a different array of lines than the previous target array.

Under post-cue only conditions, the fixation cross was visible for a total of 200ms. This was then followed by the presentation of the target array for 150ms. At target array offset, a screen containing only the fixation cross re-appeared for 300ms followed by the onset of one of the cue conditions. Post-cues were visible for 100ms. At post-cue offset, the delay period began and lasted for 900ms. Following the delay period, the comparison screen appeared.

Under pre- plus post-cue conditions, the initial fixation cross was followed by the onset of the pre-cue for 100ms. At cue offset, the target array was displayed for 150ms. This was followed by a fixation cross for 300ms. After the 300ms interval, the same-size cue that was presented previously was presented again as a post-cue for 100ms. Once the post-cue disappeared, the delay period began and lasted for 900ms. At the end of the delay period, the comparison screen appeared. Participants had 2000ms to make a response. The failure to make a response was treated as an error.

A practice session of the task was administered at the start of the experimental session. The practice session was identical to the actual experiment except for three differences. First, it was of a shorter duration, with participants only performing 8 trials of each cue condition (40 trials total), while the actual experiment required the completion of 180 trials per cue condition (900 trials total). Most importantly, the practice session differed from the actual experiment in that feedback (i.e., accuracy and reaction time) was presented in a screen that appeared for 1000ms. Feedback was provided to expedite learning for the task on practice trials but was not provided on experimental trials.

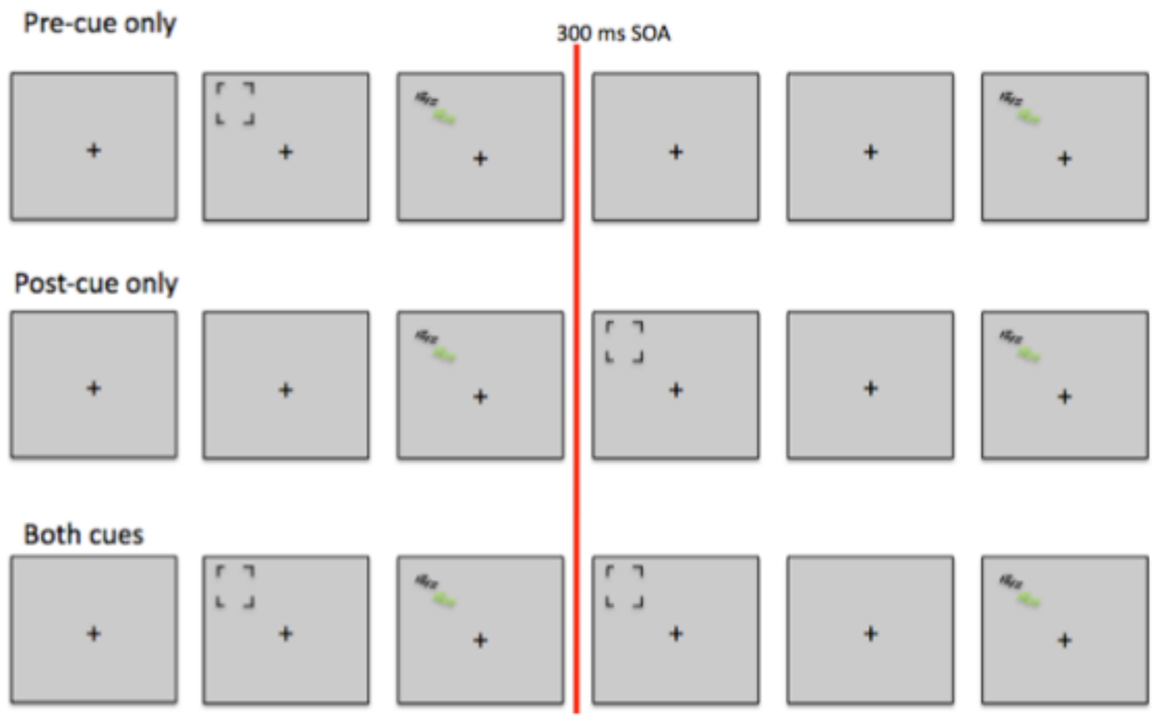


Figure 4. Diagram of the cued delayed match to sample task used in Experiment 1

Results

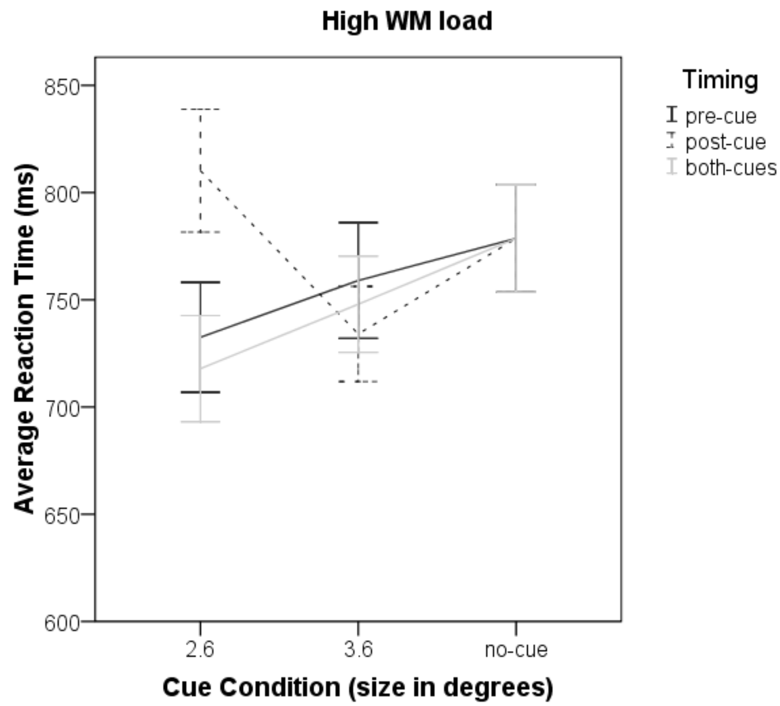
Both RT and accuracy results were analyzed. Although RT is more sensitive to the concentration of attentional resources (Eriksen & St. James, 1986), accuracy is usually the behavioral measures of choice in WM experiments. Given the difficult nature of the task, it was likely that accuracy would provide the most appropriate results.

All repeated measures ANOVAs were corrected for violations of sphericity when necessary.

REACTION TIME RESULTS

A 2 (WM Load) by 3 (Cue Condition) by 3 (Timing) omnibus repeated measures ANOVA was conducted. There were significant main effects for WM Load ($F(1,28) = 70.3$, $p < 0.01$, $\eta^2 = 0.72$), Cue Condition ($F(2, 56) = 16.59$, $p < 0.01$, $\eta^2 = 0.37$), and Timing

($F(2,56) = 14.05$, $p < 0.01$, $\eta^2 = 0.33$) as well as significant interactions of Cue Condition by Timing ($F(4,112) = 14.08$, $p < 0.01$, $\eta^2 = 0.34$) and Cue Condition by Timing by WM Load ($F(4,112) = 7.2$, $p < 0.01$, $\eta^2 = 0.21$; see Figure 5). Examination of the means showed that increased WM Load resulted in slower performance (low, M = 674.02; high, M = 754.33ms). Planned comparisons with Bonferroni corrections showed that performance was slowest under no-cue conditions compared to the 2.6° or 3.6° cue conditions (no-cue versus 2.6°, $F(1,28) = 18.37$, $p < 0.05$; no-cue versus 3.6°, $F(1,28) = 29.40$, $p < 0.05$).



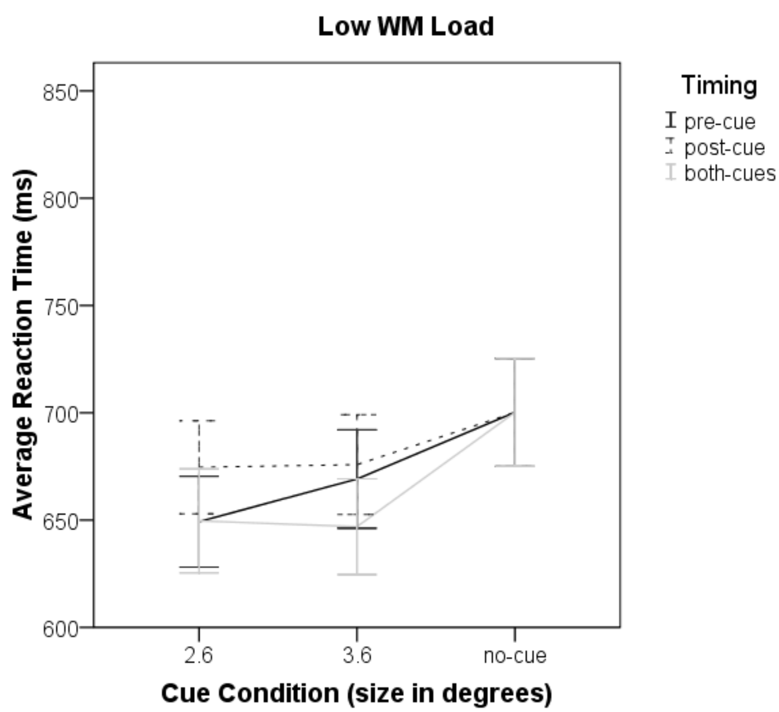


Figure 5. RT plotted as a function of Cue Condition and Timing
(Top graph is high WM Load and bottom graph low WM Load)

ACCURACY RESULTS

An omnibus 2 (WM Load) by 3 (Cue Condition) by 3 (Timing) repeated measures ANOVA was also performed on accuracy. There were significant main effects for WM Load ($F(1,28) = 225.6$, $p < 0.01$, $\eta^2 = 0.89$), Cue Condition ($F(2, 56) = 5.58$, $p < 0.02$, $\eta^2 = 0.17$), and Timing ($F(2, 56) = 28.29$, $p < 0.01$, $\eta^2 = 0.50$). Additionally, all interactions were significant (Cue Condition by Timing, $F(4,112) = 9.2$, $p < 0.01$, $\eta^2 = 0.25$; WM Load by Timing, $F(2,56) = 10.44$, $p < 0.01$, $\eta^2 = 0.27$; Load by Cue Condition, $F(2, 56) = 5.36$, $p < 0.02$, $\eta^2 = 0.16$; Cue Condition by Timing by WM Load, $F(4,112) = 9.9$, $p < 0.01$, $\eta^2 = 0.26$). See Figures 6, 7, and 8 for illustrations of these results. Examination of the means showed that increased WM Load resulted in less accurate performance (low, $M = 0.88$; high, $M = 0.75$).

The results of the omnibus repeated measures ANOVA RT and accuracy were similar in that they both showed significant main effects for all factors and a significant three way interaction. However, this study was targeted at examining the effect of a manipulation of WM load on VA. Given that accuracy is generally the behavioral measure used in WM studies all remaining analyses were conducted on accuracy data.

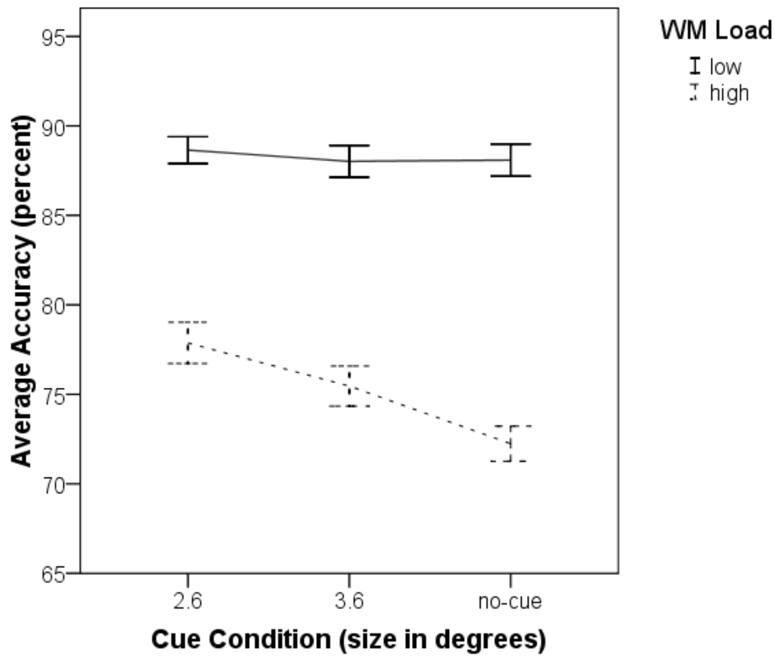


Figure 6. Accuracy plotted as a function of Load and Cue Condition

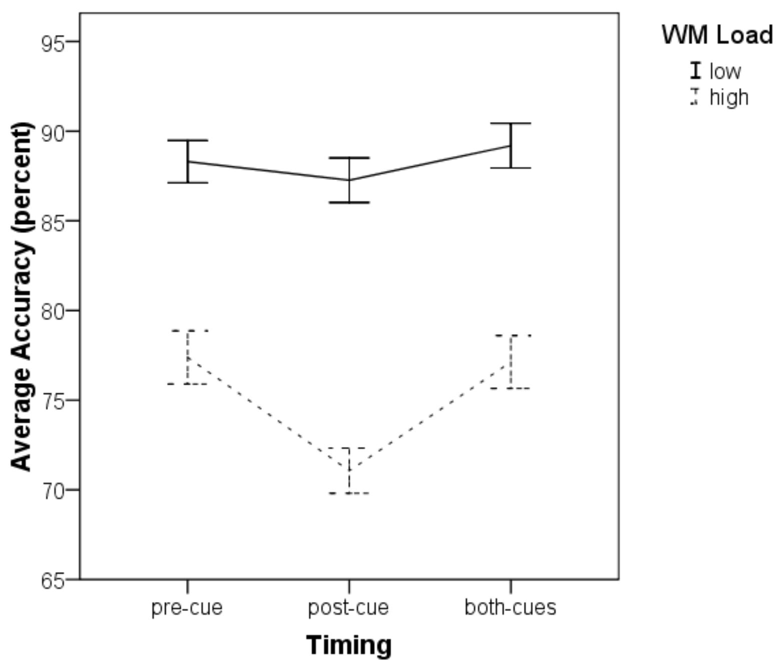


Figure 7. Accuracy plotted as a function of Timing and WM Load

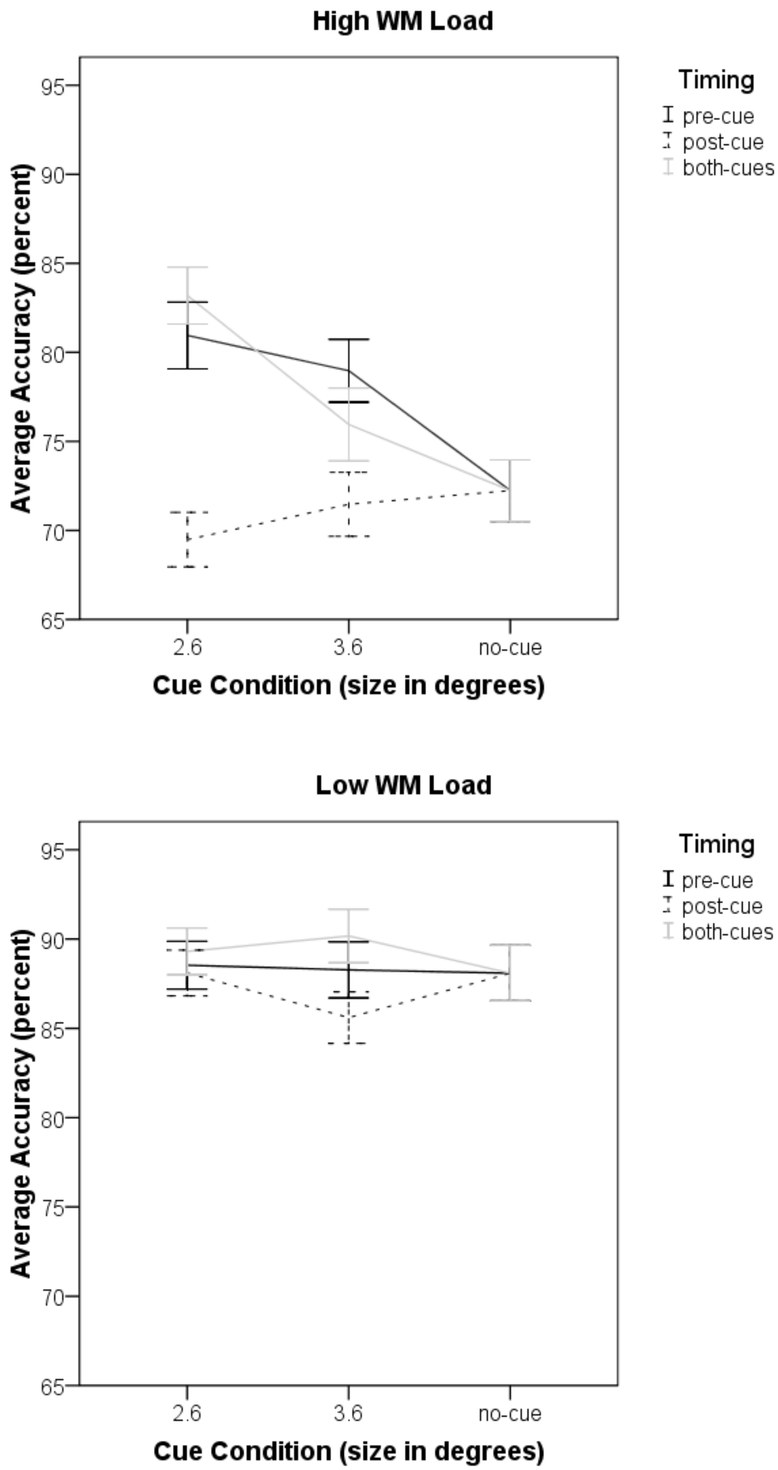


Figure 8. Accuracy plotted as a function of Cue Condition and Timing
(Top graph is high WM Load and bottom graph is low WM Load)

Given that the results from the no-cue conditions were the same, an omnibus repeated measures ANOVA was conducted without the no-cue conditions, resulting in a 2 (WM Load) by 2 (Cue Condition) by 3 (Timing) ANOVA on both RT and accuracy. The removal of the no-cue condition did not alter the pattern of significance of the above results, suggesting that these effects are not dependent on the absence of a cue.

FOLLOW-UP ANOVAS

Based on the hypothesis that manipulation in WM Load would modulate the effect of the timing of attentional deployment on performance and also on the significant interactions in the omnibus ANOVA, follow-up 3 (Timing) by 2 (Cue Condition) ANOVAs were conducted for each level of WM Load. Given the prediction of our hypothesis that the effect of Timing would differ as a function of WM Load, only the levels of Cue Condition that contained a cue were used for these analyses (i.e., all levels of Cue Condition except no-cue). The 3 by 2 ANOVA on data from low WM Load conditions showed no significant main effects or interactions after corrections for violations in the assumption of sphericity. The 3 by 2 ANOVA on data from high WM Load conditions showed significant main effects of Timing ($F(2,56) = 26.54$, $p < 0.01$, $\eta^2 = 0.49$) and Cue Condition ($F(1,28) = 9.05$, $p < 0.01$, $\eta^2 = 0.24$), as well as a significant interaction of Timing by Cue Condition ($F(2,56) = 6.66$, $p < 0.01$, $\eta^2 = 0.19$). Based on the main effect of Timing and the predicted effects of that factor, pairwise comparisons were conducted to probe the Timing main effect, as this was the effect of interest. These showed that the post-cue produced significantly different effects compared to the pre-cue and the both-cue conditions (pre-cue versus post-cue, $F(1,28) = 38.21$, $p < 0.01$, $\eta^2 = 0.57$; both-cues versus post-cue, $F(1,28) = 37.06$, $p < 0.01$, $\eta^2 = 0.57$). Examination of the means revealed that performance was significantly worse under post-cue conditions than during pre- or both-cue conditions (pre-cue, M = 79.96, SD = 8.84; post-cue, M = 70.47, SD = 7.53; both-cues, M = 79.57, SD = 8.92). This can be seen in Figure 9.

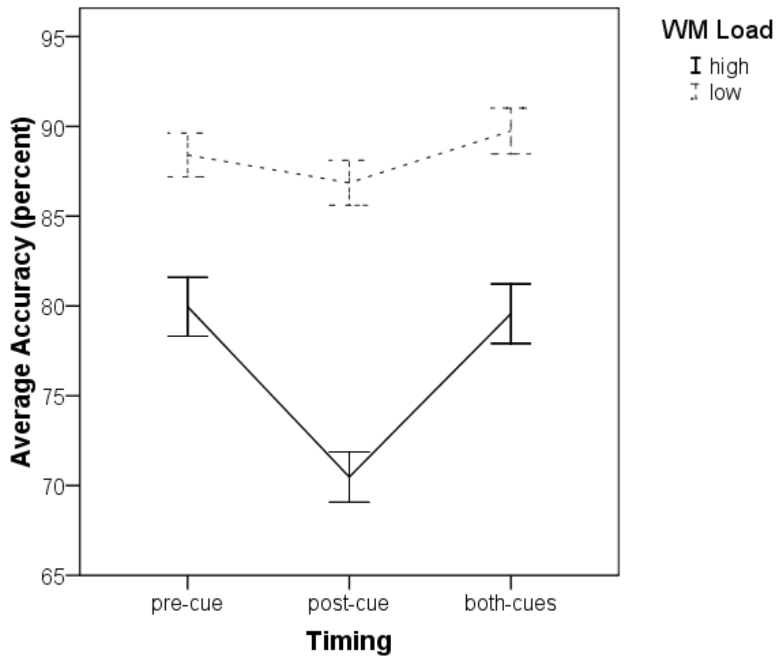


Figure 9. Accuracy plotted as a function of Timing and WM Load during 2.6° and 3.6° cue conditions.

Discussion

Experiment 1 was designed to test a prediction of the hypothesis that WM and VA form an integrated process when simultaneously deployed. Under the integrated view, cues presented before target presentation would affect both target encoding and maintenance. Post-cues would only affect maintenance and would lead to the re-encoding of the stimulus. Under the parallel view, cues presented before target presentation would mainly affect target encoding. Post-cues would only affect maintenance. If WM and VA become integrated, then cues presented early in a WM trial would be able to affect multiple stages of processing, allowing them exert a greater benefit on performance compared to cues presented later in the trial. Further, WM load was predicted to heighten the difference between the effect of deploying VA prior to or following the presentation of a target, because the new process formed by WM and VA operates on the shared resources of these processes. Thus, the tax on WM resources resulting from an increase in WM load is ameliorated through the use of resources typically allocated to VA. The alternative, parallel viewpoint predicted that effects of pre- and post-cues would not be influenced by WM load. This view further suggests that when both pre- and post-cues are presented, the heightened processing benefit following from the presentation of the pre-cue is not sustained throughout the trial. The presentation of a subsequent post-cue would therefore act to disrupt processing.

The results were generally in line with the predictions of the integrated view. The presentation of pre-cues or of both pre- and post-cues enhanced performance compared to presentation post-cues alone. A previous study has shown that behavioral performance was similar regardless of whether VA is deployed before or after stimulus presentation while neurophysiological data show differences (Griffin & Nobre, 2003). Specifically, the use of pre- and post-cues resulted in similar patterns of costs and benefits to performance. However, brain wave data showed that the post-cue was uniquely associated with early effects over frontal electrodes. It was postulated that this might reflect the orienting to a mental representation in WM. In the present study, we found that performance differed depending on whether VA was deployed prior to or following target presentation, but this was seen only under the high WM Load condition, with higher WM accuracy under pre-cue compared to the post-cue conditions. Thus, data from Experiment 1 provides evidence that VA affects all stages of processing following its deployment, but this is only observable behaviorally when WM resources are strained under high load. This supports the integrated view in suggesting an integrated cognitive process in that it suggests that the taxing of WM resources that occurs in the high WM Load condition results in the subsequent use of VA associated resources.

The observed difference between the effects of pre-cues and post-cues on behavioral performance is in contrast to a previous study, which did not find behavioral differences due to the timing of cue deployment (Griffin & Nobre, 2003). We suggest that the absence of differences between pre-cues and post-cues in the Griffin and Nobre (2003) study was due to weak demands on WM resources. However, that study did not manipulate WM load. Our speculation is supported in that we also found no differences between pre-cues and post-cues when WM load was low. Our conclusion is further supported by the perceptual load theory, which states that distracting items are not processed when perceptual load is high due to a lack of available spatial-perceptual selective attention resources, while when perceptual load is low, exclusion of distractors is dependent on higher level cognitive functions, such as WM (e.g., Lavie, 1995; Lavie, Hirst, de Fockert, & Viding, 2004). When perceptual load is low—as it is assumed to be in this experiment—and WM resources taxed, distracting information is processed, and performance suffers (Lavie, *et al.*, 2004). The perceptual load theory therefore suggests that the availability of VA processing resources that occur as a result of the integration of WM and VA are used to improve performance through the suppression of distracting information. Further, given that an integrated process formed, the pre-cue and both-cues condition allowed the resources associated with VA to be activated for a longer period of time than the post-cue condition, resulting in an extended duration of suppressed distractor processing. Thus, the perceptual load theory would predict that when WM load was low, VA resources would not be necessary for efficient performance, and so there would be no difference as a function of the duration of VA resource availability. However, when WM was high it would predict performance would be better in the pre-cue and post-cue conditions than the post-cue condition. Both of these predictions mirror the experimental observations.

The similarity in effects of the pre-cue and the pre-cue plus post-cue conditions was notable. We speculate that, due to the timing of their deployment, the condition that presented only pre-cues and the condition that presented both pre-cues and post-cues within the same trial have similar effects on encoding and maintenance. In contrast, the condition that presented only post-cues affected maintenance alone. This supports the integrated view in that it suggests that the pre-cue-driven deployment of VA prior to stimulus presentation enhanced performance whether a post-cue was also presented or not, as the two conditions had similar effects on processing.

Further support from the integrated view is evident in the observation of an effect of cue condition only when WM Load was high. The manipulation of WM Load resulted in the modulation of the effects of two aspects of VA—timing of deployment and attentional constriction. This supports the integrated view's prediction that when the integrated process is formed and the resources of either WM or VA are taxed, there will be effects on all facets of the other process that are dependent on the shared resources on which the integrated process operates. The experiments in this dissertation do not allow for any conclusions regarding nature of these facets and the shared resources but will be speculated on in chapter 5.

Additionally, under high load conditions, post-cues were found to impair WM performance when compared to the no-cue condition. In contrast, the pre-cue or both-cues conditions enhanced performance. This provides further evidence that WM and VA share resources in that the both-cues condition used a post-cue and yet was associated with enhanced WM performance. We suggest that the difference in performance associated with conditions that used a post-cue, post-cue and both-cues, is due to the integrated process. The enhancing effects of the pre-cue, which is included in the both-cues condition, are maintained through subsequent stages of processing. We speculate that the pre-cue may protect the target in some way from interference effects of the post-cue. Consistent with that, under the both-cue condition, the post-cue did not appear to interfere with target maintenance. In contrast, when the post-cue was presented alone within a trial, target disruption or interference occurred.

The integrated and parallel views did have predictions in common. They both predicted that performance would be enhanced with lower WM load and with greater cue precision. The results of this study mostly supported these predictions based on previous findings. The one difference was that under low load, there was not a significant effect of Cue Condition, suggesting that cue size and/or presence did not affect performance. This is likely due to the fact that performance was largely close to ceiling during low WM Load trials. Given that the focusing of VA on targets serves to enhance processing, if ceiling performance has already been achieved, VA cannot further enhance performance. This also lends support to the integrated theory by demonstrating that WM load is capable of inducing changes in the effects of VA.

In sum, the results of this experiment showing that effects of pre-cues protect the target from interference, especially under high load, provide support for the view that WM and VA form an integrated cognitive process when simultaneously deployed. This is a unique finding in that while current theories suggest a close relationship between WM and VA none of them provide a testable theory of the nature of this relationship. Specifically, both the embedded process (Cowan, 1999) and multicomponent (as reviewed in Baddeley, 2007) models of WM assign attention a large role within WM, but do not make predictions regarding whether or not they form a unique process. These models focus instead on delineating the responsibilities of attention within VA.

3. EXPERIMENT 2

Background

Based on our hypothesis that VA and WM become integrated when deployed together, we predicted that the manipulation of WM would lead to graded changes in VA. Experiment 2 was designed to test this prediction. To do this, Experiment 2 focused on a property fundamental to VA: the distribution of attention in space. Here, the effect of WM load on the shape of the attentional distribution was probed through the use of distractors (Cutzu & Tsotsos, 2003; Müller, Mollenhauer, Rösler, & Kleinschmidt, 2005).

Previous evidence suggests that visuospatial attention is distributed with a suppressive annulus surrounding the focus of attention, meaning that performance is best at the center of the attentional focus, but suffers in the immediately surrounding area, with less suppression further from this area (Cutzu & Tsotsos, 2003; Müller, *et al.*, 2005). Previous research has unsuccessfully attempted to manipulate this shape by modulating perceptual load (Müller, *et al.*, 2005). Here, we manipulated WM to assess whether graded changes in WM load lead to graded changes in VA, if so, that would suggest that the two constructs form a new process when simultaneously deployed. However, if the parallel view is correct and the two processes are interactive, but independent, the manipulation of VA or WM alone will result in broad, not graded, changes in the other.

The paradigm in this experiment capitalizes on this difference between the views by examining the effect of a manipulation in WM on a property of VA—the attentional distribution. The parallel view suggests that increasing WM load will lead to only a broad change in the attentional distribution—increased WM load will result in enhanced processing in the center of attentional focus. The integrated view, however, suggests that manipulating WM load will lead to a difference in the shape of the distribution of the attentional focus—likely not only enhanced processing in the center of the attentional focus, but also a steeper but narrower suppressive annulus. It was also predicted that the results of this study would replicate the previously established observation that performance suffers from increased WM load.

Methods

PARTICIPANTS

Participants were 22 undergraduate students at George Mason University (8 male). The age range was 18–26 with an average age of 20.75. All participants received research credit in exchange for their participation.

STIMULUS DISPLAY

This design was intended to identify whether a manipulation in WM would result in inherent changes to VA. This was operationalized by observing the effect of manipulations in WM load on the shape of the attentional distribution, where the shape of the distribution was probed through the use of distractors at varying distances from the target. In this study there were two possible levels of WM Load (i.e., low and high) and seven levels of Distance (i.e., 0°, 1.3°, 2.6°, 3.9°, 5.2°, 6.5°, and 7.8°).

Stimuli were random arrangements of the letters E, F, X, and O on a semi-circle (diameter = 4.5° degrees of visual angle). Letters were black and were presented within black outlines of squares (side length = 1.2° of visual angle). A square enclosed an arrangement of either two or four of these letters and was located at seven different spots around this semi-circle, with 1.3° of visual angle between each position. Each letter measured 0.6° by 0.6° of visual angle. When two letters were present, they were positioned horizontally adjacent to each other in the center of the square. When four letters were present, they were evenly spaced and each was relegated to one corner of the square (i.e., upper left, upper right, lower left, or lower right). All letters were black and presented on a gray background.

PROCEDURES

Each trial began with a 100ms presentation of a fixation cross in the center of the screen. The fixation cross remained visible throughout the task and served as the mid-point of the imaginary circle in which the stimuli would appear. The stimuli were then presented. Participants were instructed to remember the letters in the square in the uppermost position on the semicircle. There were six additional squares containing letters arranged on the semi-circle (see Figure 10). On low load trials, all squares contained two letters, while on high load trials, the squares contained four letters. Importantly, there were letter pairings that could appear within each square—E's and F's or X's and O's. The uppermost position always contained a random assortment of E's and F's. Depending on the condition, either five or all six of the remaining squares would contain a random assortment of X's and O's. During the trials in which only five of the remaining display points contained X's and O's, the sixth position would contain E's and F's, which will be hereby referred to as the distractor stimulus (see Figure 11). This second stimulus display containing E's and F's was presented randomly at one of the six display points such that all positions were equally represented at the conclusion of the experiment. This display appeared for 150ms. After the stimulus display, a delay screen appeared which contained only the fixation cross for 900ms. Participants were asked to remember the letters in the uppermost position during this time.

Following the delay period, the comparison screen appeared and participants were asked to identify with a button press whether any of the letters in the uppermost position had changed. If there was a change, only one letter would have changed and only from E to F or F to E. The distractor stimulus array, which also contained E's and F's, would either change or stay the same in the opposite manner of the to-be-remembered stimulus. Thus, if the to-be-remembered stimulus changed, then the distractor stimulus with E's and F's would not contain a letter change. All stimulus positions containing X's and O's never contained letter changes. Participants had 2700ms to identify whether a letter change occurred in the uppermost position on the semi-circle. Once a key was pressed, a new trial began immediately.

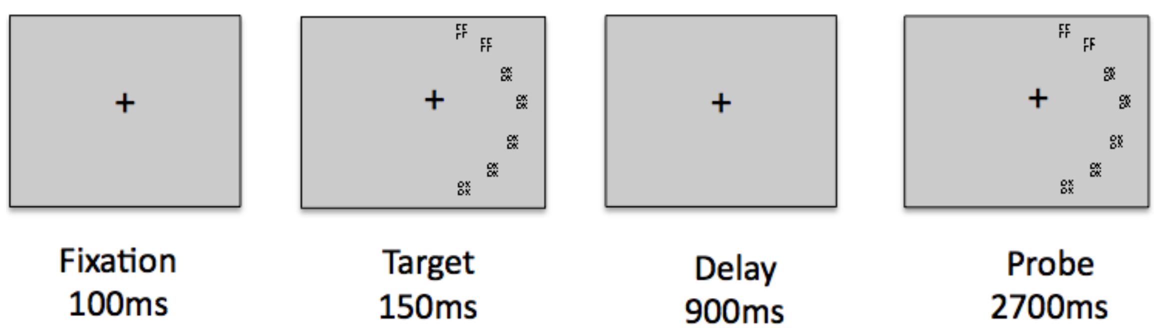


Figure 10. Diagram of the attentional probe delayed match to sample task used in Experiment 2

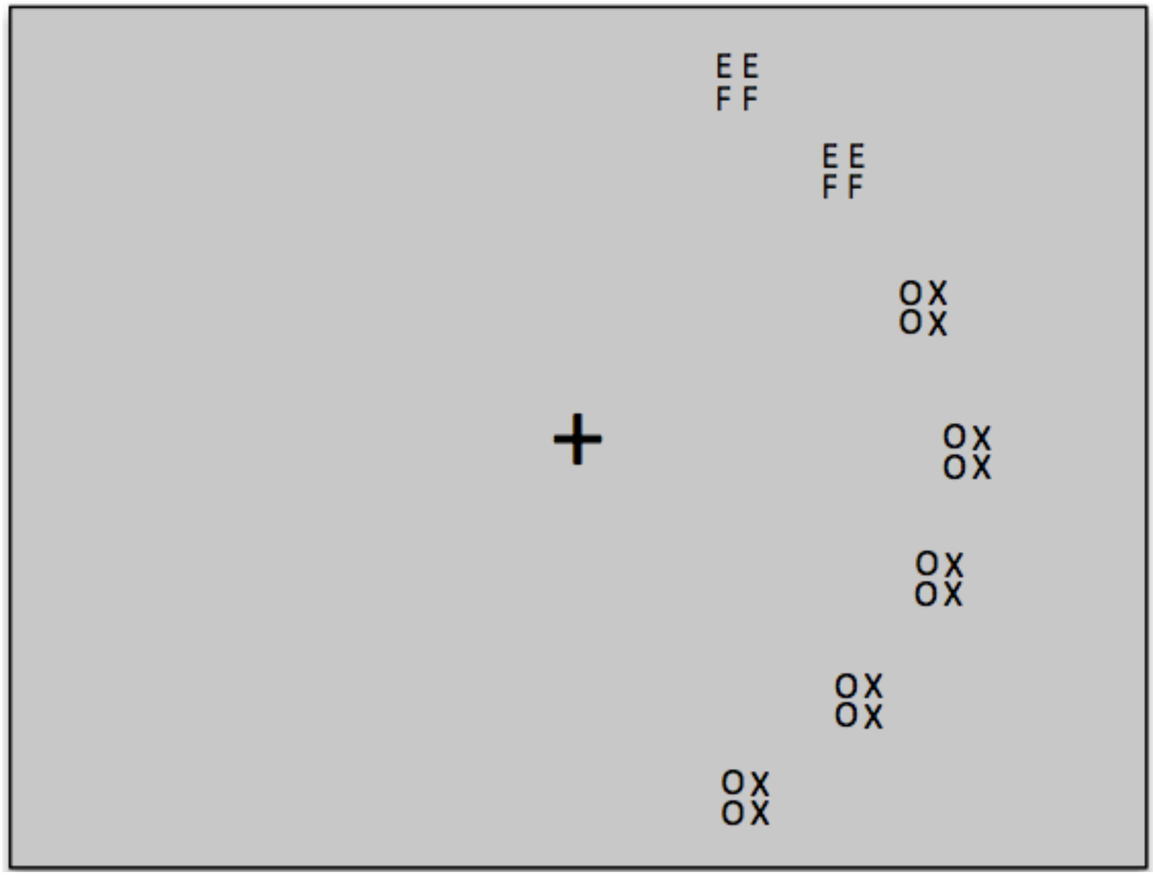


Figure 11. Diagram of the probe event to be used in Experiment 2 with the distractor present at the 1.3° distance

Prior to participation in the experiment, participants were given 42 practice trials: 21 of each load (low and high) and 3 of each possible distractor stimulus position (all additional six spaces as well as a condition in which no distractor stimulus was presented). Practice trials were identical to the actual experiment with two exceptions. First, participants were given feedback during practice to help facilitate learning. Feedback was not given in the actual experiment. Second, in the actual experiment there were a total of 560 trials with 280 each of high and low load and 80 trials of each possible distractor stimulus position.

Results

ACCURACY

An omnibus 2 (WM Load) by 7 (Distance) ANOVA was conducted on accuracy. There were 2 levels of WM Load: low and high. The 7 levels of Distance represented the location of the distractor stimulus on the semi-circle (i.e., either no distractor stimulus, or one of the 6 other distractor stimulus locations on the semi-circle). Results showed significant main effects for both WM load ($F(1,21) = 39.94$ $p < 0.01$, $\eta^2 = 0.66$) and Distance ($F(6,126) = 6.02$, $p < 0.01$, $\eta^2 = 0.22$) as well as a significant interaction between WM load and Distance ($F(6,126) = 5.30$ $p < 0.01$, $\eta^2 = 0.20$; see Figure 12).

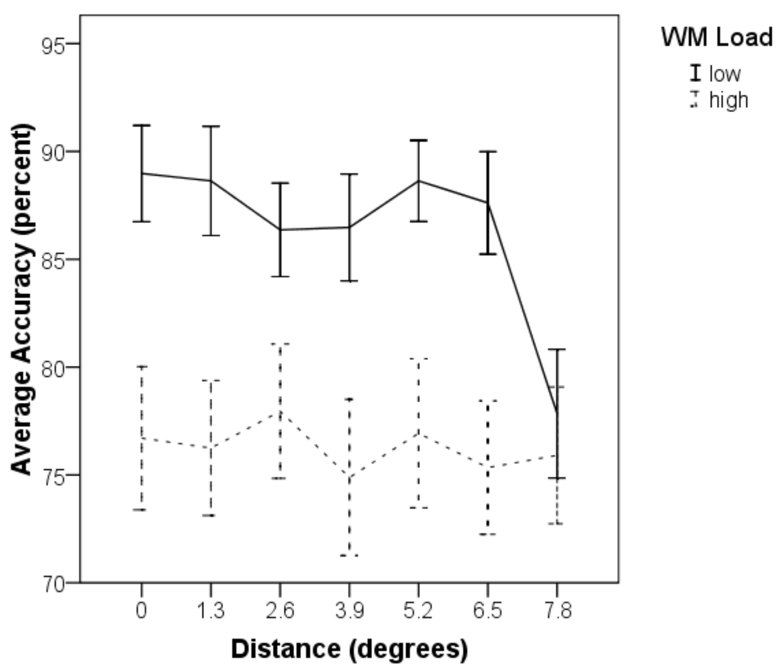


Figure 12. Accuracy plotted as a function of Distance and WM Load

REACTION TIME (RT)

An omnibus 2 (WM Load) by 7 (Distance) ANOVA was also conducted on RT. As with the omnibus ANOVA on accuracy, WM Load could be low or high and the 7 levels of Distance represented the location of the distractor on the semi-circle. Results of this analysis showed significant main effects for both WM Load ($F(1,21) = 39.77$, $p < 0.01$, $\eta^2 = 0.65$) and Distance ($F(6,126) = 3.68$, $p < 0.05$, $\eta^2 = 0.15$), as well as a significant interaction between WM load and Distance ($F(6,126) = 2.36$, $p < 0.05$, $\eta^2 = 0.10$; see Figure 13).

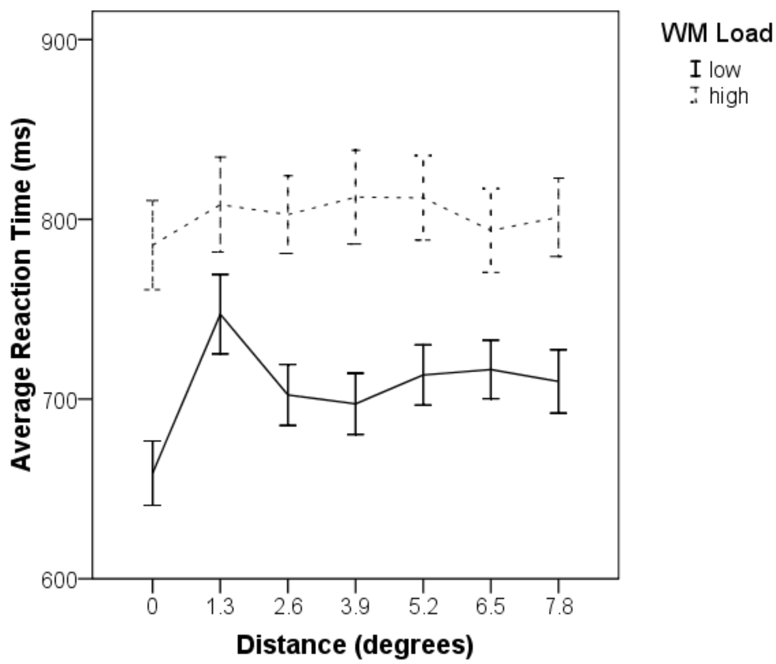


Figure 13. RT plotted as a function of Distance and WM Load

FOLLOW-UP ANOVA ON ACCURACY

In order to further explore the significant main effect of WM Load and the WM Load by Distance interaction, one-way (Distance) ANOVAs were conducted on low and high WM Load data separately. Results showed a significant main effect of Distance when WM Load was low ($F(6,126) = 9.64$, $p < 0.01$, $\eta^2 = 0.32$), but not when WM Load was high ($p > 0.05$). Because we had predicted that the distribution of attention would involve a "suppressive annulus", polynomial contrasts were performed on the low WM Load data. The result of the contrast showed that linear, quadratic, cubic, and order 4 all explained the shape of the Distance data (linear, $F(1,21) = 15.26$, $p < 0.03$; quadratic, $F(1,21) = 14.42$, $p < 0.05$; cubic, $F(1,21) = 14.12$, $p < 0.05$; order 4, $F(1,21) =$ d2, $p < 0.05$). However, the linear trend provided the best explanation for the data. The means suggested that performance decreases with increased distance (0°– M = 88.98, SD = 10.46; 1.3° − M = 88.64, SD = 11.87; 2.6° − M = 86.36, SD = 10.17; 3.9° − M = 86.48, SD = 11.62; 5.2° − M = 88.64, SD = 8.82; 6.5°– M = 87.61, SD = 11.14; 7.8° − M = 77.84; SD = 13.98). Pairwise comparisons with Bonferroni corrections revealed that under low WM Load there was only a significant difference between 7.8° and all other distances, such that performance is worst for the 7.8° distance (7.8° versus 0°, $F(1,21) − 23.54$, $p < 0.05$; 7.8° versus 1.3°, $F(1,21) − 14.78$, $p < 0.05$; 7.8° versus 2.6°, $F(1,21) − 18.56$, $p < 0.05$; 7.8° versus 3.9°, $F(1,21) − 17.82$, $p < 0.05$; 7.8° versus 5.2°, $F(1,21) − 24.70$, $p < 0.05$; 7.8° versus 6.5°:, $F(1,21) − 23.24$, $p < 0.05$).

FOLLOW-UP ANOVA ON RT

Justified by the significant main effect of Load and the interaction of Load × Distance on RT, one-way ANOVAs were conducted on low and high WM load data separately. These ANOVAs only showed a significant effect of Distance for low-load data ($F(6,126) = 5.53$, $p < 0.01$, $\eta^2 = 0.21$), but not for high-load data ($p > 0.05$). To explore the prediction of a "suppressive annulus," polynomial contrasts were performed to identify the shape of the distribution. These contrasts showed that while quadratic, cubic, order 4, and order 5 trends all provide appropriate trends of the data, order 4 provides the best estimate of the shape of the Distance effect at low levels of WM load (quadratic, $F(1,21) = 5.72$, $p < 0.03$; cubic:, $F(1,21) = 5.27$, $p < 0.05$; order 4, $F(1,21) = 13.72$, $p < 0.01$, order 5, $F(1,21) = 4.56$, $p < 0.05$). Data with an order 4 trend has two peaks, likely represented here by distance 1.3° and distances 5.2° and 6.5°. Pairwise comparisons with Bonferroni corrections were then conducted in order to better understand the nature of the significant main effect of distance for low load data. Under low load, performance was best (i.e., fastest) when there is no distractor (no distractor vs. 1.3°, $F(1,21) = 22.12$, $p < 0.01$; no distractor vs. 2.6°, $F(1,21) = 11.63$, $p < 0.01$; no distractor vs. 3.9°, $F(1,21) = 10.41$, $p < 0.01$; no distractor vs. 5.2°, $F(1,21) = 13.04$, $p < 0.01$; no distractor vs. 6.5°, $F(1,21) = 14.67$, $p < 0.01$; no distractor vs. 7.8°, $F(1,21) = 16.45$, $p < 0.01$). Additionally, performance was significantly slower when the target was 1.3° from the distractor compared to when it is 2.6° or 3.9° away from the distractor (1.3° vs. 2.6°, $F(1,21) = 5.26$, $p < 0.05$; 1.3° vs. 3.9°, $F(1,21) = 5.42$, $p < 0.05$).

Discussion

Experiment 2 examined one prediction of the hypothesis, that the new process formed by WM and VA operates on resources typically allocated to each process individually. Experiment 2 examined the effect of WM load on the distribution of VA to determine whether WM and VA form a new process or simply interact when simultaneously deployed. The integrated view predicts that if WM and VA form a new process when simultaneously deployed, then this process would act on the shared resources of both processes. This would suggest that manipulating WM load fundamentally alters the distribution of attention. If the two processes are only interactive, as is posited by the parallel view, then the manipulation of WM load would lead to a general enhancement of the benefit to target processing in the center of attentional focus, but would not further alter the way VA is distributed in space. The results from this study generally supported the integrated view by showing that the shape of the attentional distribution changed as a function of the level of WM load. Additionally, previously reported effects of VA and WM were observed: the presence of attentional cueing and decreasing WM load enhanced performance.

Knowledge of the shape of the distribution of attention has evolved over the years. It was first suggested that VA acted as a spotlight, with the attentional distribution tightly focused on a cued location, with no attentional enhancement outside this area (Posner, *et al.*, 1980). This view was amended by the zoom lens view, which extended the spotlight view by suggesting that the area of focus can be modulated, based on task demands to be either to be tightly focused, as in a spotlight, or to be more broadly distributed across space (Eriksen & St. James, 1986; Eriksen & Yeh, 1985). Another view of the attentional distribution is that it is distributed as a gradient (Downing, 1988), with the steepness of the gradient varying with task difficulty. However, given that all of these postulated distributions lead to the prediction that performance decreases linearly with distance from attentional focus, they are unable to account for the ability of stimuli located just outside the area of attentional focus to influence performance. In response to this, it has recently been observed that, in certain situations, the center of the attentional focus is surrounded by a suppressive annulus (Cutzu & Tsotsos, 2003). It was thought that while any of these shapes may be observed in this experiment the suppressive annulus was most likely given previous evidence.

The examination of the effects of WM load on the attentional distribution allowed for a direct comparison of the predictions of the integrated and parallel views. The integrated view suggests that manipulations of one process should result in graded changes in the second, such that if WM load is manipulated, there should be a change in the way VA is distributed in space. The parallel view instead posits that a change in one process would only result in general, not graded, changes in the other. This would manifest itself as a change in the strength of the effect of the focus of attention with all other aspects of the distribution remaining constant. The results of this experiment supported the integrated view. While when WM load was low there appeared to be a region of attentional focus surrounded by a suppressive annulus, under high WM load there was a more dispersed distribution of attention. It is not surprising that VA was so widely dispersed under high WM load, given that past research has shown evidence of such a distribution. Specifically, in WM tasks, it has been shown that a pre-cue that encompasses some background information was more beneficial to performance than one that only encompassed the target (Greenwood, Lambert, *et al.*, 2005), while in VA tasks, a pre-cue encompassing just the stimulus is associated with optimal performance (Greenwood & Parasuraman, 1999, 2004). This suggests that the distribution of attention differs depending on whether a WM or VA attention task is used. Given that Experiment 2 combined both WM and VA, the integrated view would predict that the observed distribution will be dependent on which resources are currently being taxed. Thus, this marked difference in the shape of the attentional distribution as a function of WM load is evidence that WM is capable of inducing fundamental changes in VA, suggesting that WM and VA become integrated when simultaneously deployed.

While results of this study demonstrated that the shape of the attentional distribution changes with manipulations of WM load, supporting the integrated view, the direction of this effect was not as originally predicted. Previous research suggested that the constriction of attention around an area might be of greater benefit when WM load is high compared to low (Chen & Chan, 2007). This suggests that increased WM load would result in a narrower, stronger area of attentional enhancement and annulus when WM load is high. Instead, the present results showed that when load was high, there was a diffuse attentional distribution. However, past research has demonstrated that the optimal size of attentional focus is dependent on the task, with WM tasks benefiting more from pre-cue sizes that include ground information in addition to the figure (Greenwood, Lambert, *et al.*, 2005). It has been argued that this observation is attributable to stronger processing when both the figure and ground information are encoded. This may be particularly true under high WM load conditions the added benefit of processing background information results in a broad attentional distribution.

This study demonstrated the replication of some previously established WM and VA related phenomena. For example, this experiment not only found evidence of a region of suppression surrounding the attentional focus, but also provided evidence supporting previous findings that decreased WM load results in enhanced performance. This was found to be true regardless of measurement (i.e., RT or accuracy). Additionally, performance was worst when WM load was high and best when no distractor was present, phenomena commonly reported in the literature.

While the existence of a suppressive annulus surrounding the area of attentional focus was predicted for the attentional distribution based on previous work (Cutzu & Tsotsos, 2003), the present experiment may have provided evidence that expands on this evidence. Specifically, the distribution of attention in the RT measure under low load was likely order 4 in nature, meaning that there were two peaks in the data, at 1.3° from the target and between 6.5° and 7.8° from the target, representing slower performance. The suppressive annulus observations would only predict a peak at 1.3°. These results suggest that at low load and extended distances, while there is a suppressive annulus surrounding the center of attention, performance may not reach an asymptote and trail off, as has been originally suggested, but instead may decline to an unknown level.

Another interesting finding is that in the accuracy data there was a decrease in performance only when the distractor was the furthest away from the target, with no evidence of a suppressive annulus or added benefit to processing in the center of attention. This was not seen in the RT data. While RT and accuracy are both measures of behavioral performance they offer very different insights into cognitive performance, with particular phenomena being better captured by one measure then the other. WM tasks typically use accuracy while VA tasks use RT (Eriksen & St. James, 1986). Here it appears as though the attentional distribution differs depending upon which measure is used. It may be the case that since WM and VA have formed an integrated process each behavioral measure is able to capture a unique view of the new process, such that the actual shape of the attentional distribution is likely to be a composite of that seen in the accuracy and RT data individually. While the results provided evidence of two different distributions, they both showed a change in the shape of the distribution when WM load is manipulated. Thus, regardless of the measure that is selected, there is support for the integrated view.

To summarize, the results of Experiment 2 support the integrated view of the relationship between WM and VA. Specifically, it was found that manipulating WM load changed that the way VA attention was distributed in space. Results of Experiment 2 also support past research, demonstrating the benefit of decreasing WM load and the existence of a region of attentional enhancement immediately surrounded by a region of attentional suppression.

4. EXPERIMENT 3

Background

The third experiment in this dissertation was designed to test one prediction of the hypothesis that WM and VA become integrated when deployed simultaneously. If the hypothesis were accurate, then this new process would lead to the sharing of processing resources typically allocated to WM and VA individually. Thus, the hypothesis would predict that the deficit in performance that results from the taxed WM resources in the low-WMC group could be ameliorated through the degree of availability of VA resources. The design was based on a previous study that found a relationship between the ability of individuals to filter out distracting items (measured in patterns of posterior scalp voltage) and their WMC (Vogel, *et al.*, 2004; McCollough, *et al.*, 2007). We adapted that design by directing VA in advance to targets of the WM task. We hypothesized that due to the ability of the integrated process to access the resources typically allocated to VA and WM individually, VA would affect the relationship between filtering efficiency and WMC.

The contralateral delay activity (CDA) is a useful measure with which to assess the relationship between WM and VA. The CDA is defined to be an EEG difference waveform recorded during the delay period of a WM task that is maximal over posterior lateral regions. It is calculated by subtracting the voltage at electrodes located ipsilateral to the target stimuli from the voltage at electrodes located contralateral from the target stimuli. Previous work has shown the CDA to be sensitive to WM load (Vogel, *et al.*, 2004; McCollough, *et al.*, 2007). Our work has shown the CDA to be sensitive to both VA and WM, with CDA amplitude becoming increasingly positive with increased pre-cue precision and increasingly negative with increased WM load. When both WM and VA were manipulated, there was an effect of VA regardless of WM load, such that the presence of a pre-cue resulted in a less negative CDA. Additionally, when WM load was high there was also an effect of the size of the pre-cues, such that the CDA became less negative with increased attentional constriction (Clarke, *et al.*, 2010). Given that the CDA has been found to be sensitive to both WM and VA, it is likely to be an appropriate measurement tool when attempting to understand the nature of the relationship between these two processes.

If, as hypothesized, an integrated process were formed when WM and VA are simultaneously deployed, then the two processes would come to share common resources. Sharing of resources would mean that manipulations in one process lead to graded changes in the other process. Should this be the case, then manipulation of pre-cue precision should lead to graded differences in the relationship between WMC and filtering efficiency, such that the greater the demand on the resource, the more VA would influence WM and/or vice-versa. Alternatively, if WM and VA simply interact, then resources would not be shared, and thus a manipulation in one process would not lead to graded changes in the other. Only the presence of the pre-cues, and not pre-cue size, would exert effects on distractor filtering efficiency.

Following Vogel, *et al.* (2005), this study recorded EEG during a computer-based delayed match-to-sample task, which manipulated WM load over 3 levels—two targets, four targets, and a distractors-present condition. The latter consisted of two to-be-remembered targets along with two distractors. CDA amplitude was used as a measure of WM load. Vogel and colleagues found that for individuals with low-WMC, the CDA amplitude of the distractors-present condition was similar to that of the four targets condition, suggesting that these low-WMC individuals were processing the distractors. In contrast, for individuals with high-WMC, the CDA amplitude of the distractors-present condition was similar to the two targets condition, suggesting that only the high-WMC group were effectively excluding the distractors from being processed by WM. Additionally, Vogel, *et al.* calculated a measure of filtering efficiency derived from the aforementioned averaged CDA and found that WMC was associated with the ability to exclude distracting information. These results suggest that individual differences in WMC are associated with the ability to exclude distracting information from being processed during WM maintenance.

It was also predicted that effects previously reported in the literature would be replicated, particularly those reported by Vogel, *et al.* (2005), from which this experiment was derived. When no cue is presented, low-WMC individuals would show brain wave activity indicative of an inability to exclude distracting information, while high-WMC individuals would not be affected by distracting information, regardless of cue presence. Additionally, behavioral performance should benefit from the use of pre-cues and decreased WM load.

The results of this 3rd study provided further support for the integrated view of the relationship between WM and VA. Specifically, the relationship between WMC and filtering efficiency was influenced both by cue size and by cue presence. This study also replicated two previously observed effects. First, high-WMC individuals were better able to exclude distracting information. Second, the use of cues resulted in enhanced WM performance.

Methods

PARTICIPANTS

Participants were 44 undergraduate students from George Mason University (13 male; 21 low-WMC) between the ages of 18 and 28 (mean age 20.9 years). Participants received research credit in exchange for their participation in this experiment.

MATERIALS

A medium or large 64-electrode EEG cap was placed on each participant depending on head size. Areas of the skin to which external electrodes were to be applied were prepared using an alcohol pad and then NuPrep, an exfoliating gel. All electrodes were then filled with a saline gel solution to promote connectivity.

The based task was implemented in E-Prime and the EEG data was collected using Neuroscan software. The two programs were coded so that triggers were added to the EEG data when stimuli and responses occurred. This allowed the behavioral and EEG data to be efficiently combined for analysis.

STIMULI DISPLAY (OSPAN)

Previous literature suggests that perfect serial recall from the operation–word-span task (OSPAN, Turner & Engle, 1989) is a well-established measure of WMC (e.g., Bleckley, Durso, Crutchfield, Engle, & Khana, 2003). Thus, in this study participants were screened for WMC using an online version of the OSPAN that could be run without the aid of an experimenter. The OSPAN task requires the verification of a series of simple arithmetic problems while simultaneously attempting to remember a varying number of unrelated words. This task was adapted from that designed by Turner and Engle (1989). The automated version displays a simple mathematical problem and asks the participant to select either the True or False button to indicate whether or not the problem is correct. For example, if the participant saw "$(4 \times 3) + 2 = 8$" they should click the True button to indicate that the problem is correct. Participants had unlimited time to indicate whether or not the problem was correct, but received a prompt after 6 seconds informing them, "You have taken more than six seconds for this operation" in red letters. Immediately succeeding the press of the True or False button, a new screen appeared containing a single word for 800ms. Participants were instructed to remember these words. The problem–word pairing was then repeated from two to six times. At the end of an operation–word pairing set, participants were asked to type in the words they had seen during the set in the order they were shown and then click the Next button. Once the Next button was clicked, a new series of problem–word pairings was immediately presented. Participants were able to leave blanks if they were not able to recall a word. Participants were instructed not to use any tools that could aid their performance or to rehearse the words aloud. If participants displayed an average latency for all operations that was significantly above that of the rest of the group, they were not asked to participate any further, as this was considered an indication that an aid had been used. Participants were given one practice trial consisting of two operation–word pairings. Upon completion of the practice trials, participants began the portion of the OSPAN that would be used to assess their WMC. This portion consisted of three lists of two to six operation-pairings in length for a total of 60 trials. List size order, operations, and words were randomized.

The OSPAN results in a range of different behavioral data measures. Perfect serial recall is a measure of the total number of words the participant recalled in the correct order, while also correctly naming the remaining words in that list in the correct order. Assignment of individuals to high- or low-WMC groups was based on a database containing results of the OSPAN task from several studies and universities (see e.g., Conway, *et al*., 2001; Kane, *et al*., 2001). Low-WMC individuals are those with a WM serial recall below 11, while high-WMC individuals have a serial recall of at least 18. In this study, the average serial recall for the low-WMC group was 7 and 31 for the high-WMC group.

STIMULI DISPLAY (FILTER TASK)

The design of the filter task was based on Vogel, *et al.* (2005) because that study found a relationship between WMC and the ability to exclude distracting information (see introduction; Vogel, *et al*., 2005). We predicted that attentional pre-cues would alter ability to exclude distractors from WM and hence mitigate the effect of intra-individual differences in WMC on ability to exclude distractors. To test this, our task used a match-to-sample WM paradigm with the same manipulation of WM Load (i.e., two-items, four-items, and distractors-present) used by Vogel, *et al.* (2005). In addition, our task included a Cue Condition manipulation with attentional pre-cues of various sizes (illustrated in Figure 14). All target arrays and cues were presented on a gray background within either the LVF or RVF, defined by being presented either to the left or right of a black central fixation cross. Target array positions were randomized on each trial. Three different Cue Conditions were employed: no-cue, small cue (diameter = 1.7°), and medium cue (diameter = 4.8°). The smallest cue size approached target size and the other cue sizes were selected to modulate target processing on the basis of previous work. Cues were L-brackets that formed a square. The target was always presented in the center of the cue. The targets were 1° by 1° arrays of red and blue rectangles of various orientations on a gray screen. Rectangles were randomly positioned in one of four orientations: horizontal, vertical, 45° to the left, or 45° to the right. Rectangles were shown in groups of two or four. When two rectangles were present, they were always red. When four rectangles were present, they would either all be red or half red and half blue. Participants were asked to remember the orientations of the red rectangles. Participants were seated so that their eyes were 60cm from the screen. Every 70 trials, participants were asked to take a brief break and a screen appeared, instructing them to press a key when they were ready to resume the experiment.

Each trial consisted of six events and began with the presentation of a fixation cross, which remained on all screens. Participants were directed to fixate on the cross at all times. The fixation cross was first presented along with an arrow directly above it pointing to the left or right for 200ms and was followed by the presentation of the fixation cross alone for 350ms. Then, one of the three cuing conditions, each lasting 500ms, was displayed. If a cue was presented, the target array appeared in the center of the place where the cue had previously appeared. Cues were always valid. Once the cue had vanished, the target array (two or four colored rectangles) was presented for 100ms. The fixation cross was next presented alone for a 900ms retention interval. During this interval, participants were asked to retain a memory of the orientation of the red rectangles on the half of the screen indicated by the arrow. Finally, a comparison screen appeared, again consisting of a target array, and the participants were directed to press one of two keys ("z" or "n") to indicate whether the comparison target array was the same or a different array than the target array. The test array was always in the same location as the target array. All arrays and cues were presented bilaterally. Participants had 2000ms to make a response. The failure to make a response was treated as an error. Timing of events was based on previous literature (Vogel, *et al.*, 2005; Clarke, *et al.*, 2010).

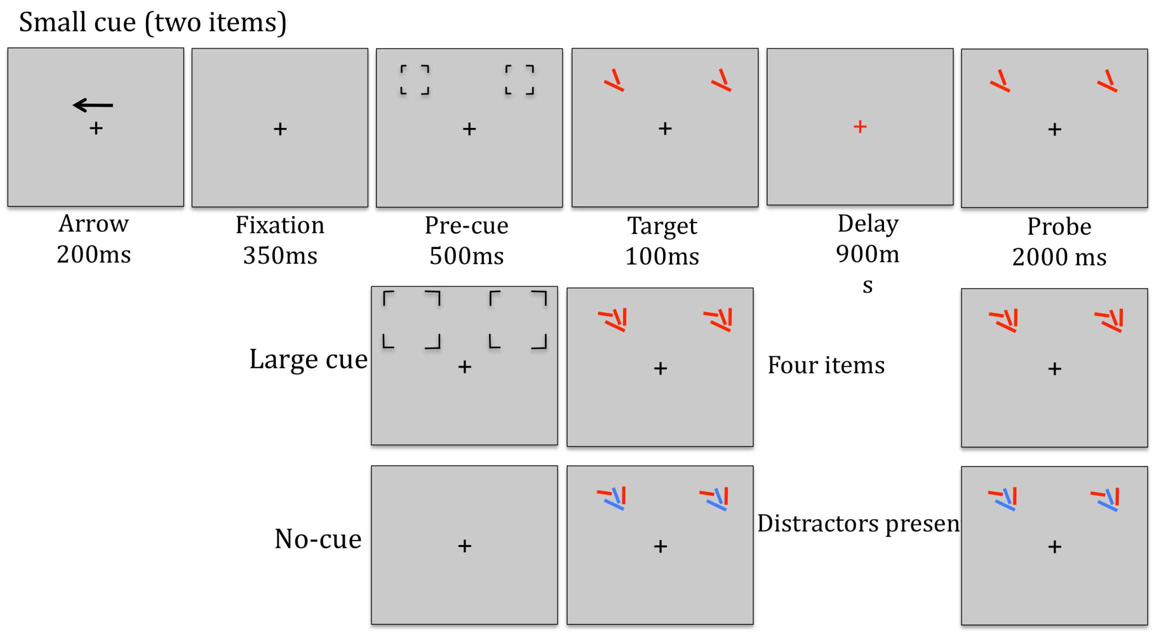


Figure 14. Diagram of the filtering efficiency task used in this experiment

Procedure

After consent was granted, each participant filled out a biographical questionnaire that contained questions about physical and mental health. Working memory capacity was assessed with an automated version of the OPSAN task. Participants were instructed to complete the OSPAN task online prior to their arrival. A practice session of the task was administered at the start of the experimental session. The practice session was identical to the actual experiment except for a few differences. First, it was of a shorter duration with participants only performing 6 trials of each cue condition–load combination (54 trials total), while the actual experiment required the completion of 78 trials per cue condition–load cue combination (702 trials total). Also, due to this shortened duration, the screens instructing the participants that they could rest, if desired, which appeared every 70 trials in the actual experiment, were not present in the practice version. Most importantly, the practice session differed from the actual experiment in that feedback (i.e., accuracy and reaction time) was presented in a screen that remained visible until the participant pressed a key to continue the session. Feedback was provided to expedite learning for the task on practice trials but was not provided on experimental trials.

EEG SETUP

Participants who were eligible for the study were connected to the EEG system. The following channels were activated for this experiment: HEO (horizontal electrooculogram, left and right), VEO (vertical electrooculogram, upper and lower), M1, M2, Ground, Reference, CZ, FZ, PZ, FPZ, FP1, F1, F3, F7, C3, P3, PO5, PO7, P7, FP2, F2, F4, F8, C4, P4, PO6, PO8, P8, O1, and O2. Once fully connected, participants received strongly emphasized instructions aimed at limiting movement both before the practice session and the actual experiment. Participants were also shown demonstrations of the effects of movement on EEG signals in an effort to increase adherence to the instructions. Participants were asked to keep their eyes focused on the fixation cross at all times and asked to blink only at one point in each trial—as they released the response key. This was done to reduce the amount of eye movement/blink-induced noise. Participants were also asked not to grind or grit their teeth. Participants who had completed the OSPAN were next asked to complete the practice session of the task. If participants were not able to complete the OSPAN prior to their arrival, for any reason, it was administered directly before the practice session. Once the practice session was complete, participants were given reminders of undesirable behavior and informed about the differences between the experiment and the practice session, as described above.

EEG ANALYSIS PROCEDURE

All EEG data were analyzed using Neuroscan. Waveform data were first re-referenced to the external mastoid electrodes M1 and M2. Once re-referenced, the data were divided into epochs from 100ms before the onset of the delay screen to 900ms after the onset of the delay screen for each Cue Condition (no cue, 1.7°, and 4.8°) and WM Load (two items, four items, and distractor). Waveform data was then filtered with a bandpass of 0.1Hz (24db/oct) to 30Hz (24db/oct). Artifact rejection was set at +/- 75uV.

Results

OSPAN

All participants were able to indicate whether a mathematical problem was correct or incorrect at least 50% of the time (mean = 92.4%). There were statistically significantly different set sizes of (a) memory spans (i.e., the maximum number of words a participant was able to recall in order; $t(42) = -8.3$, $p < 0.01$; low-WMC, $M = 3$, $SD = 1.22$; high-WMC, $M = 5.44$, $SD = 0.66$), (b) average latencies (i.e., the average amount of time taken to solve a mathematical problem; $t(42) = 3.74$, $p < 0.01$; low-WMC, $M = 851.54$, $SD = 146.04$; high-WMC, $M = 705.54$, $SD = 111.80$), (c) partial word recall (i.e., total number of words recalled in the correct order if all words in a list did not need to be in the correct order; $t(42) = -9.68$, $p < 0.01$; low-WMC, $M = 29.76$, $SD = 5.92$; high-WMC, $M = 47.22$, $SD = 6.03$) and (d) perfect serial recall ($t(28.52) = -12.03$, $p < 0.01$; low-WMC, $M = 7$, $SD = 3.33$; high-WMC, $M = 31$, $SD = 8.91$) between low- and high-WMC groups.

FILTER TASK (BEHAVIORAL)

Reaction Time

An omnibus 3 (WM Load) by 3 (Cue Condition) ANOVA was conducted on reaction time with WMC as a between subjects variable. Results revealed significant main effects of WM Load ($F(2,84) = 24.21$, $p < 0.01$, $\eta^2 = 0.36$) and Cue Condition ($F(2,84) = 22.67$, $p < 0.01$, $\eta^2 = 0.34$) and no significant interactions (see Figure 15). The between subjects effect of group was also significant ($F(1,42) = 7.82$, $p < 0.01$, $\eta^2 = 0.16$), such that those in the high-WMC group were faster than those in the low-WMC group (low-WMC, M = 773.76, SD +/- 29.89; high-WMC, M = 658.16, SD = 28.56). Pairwise comparisons were then conducted using a Bonferroni correction. These analyses showed a significant difference between the no-cue condition and all other levels of Cue Condition (no-cue versus 1.7°, $F(1,43) = 32.46$, $p < 0.05$; no-cue versus 4.8°, $F(1,43) = 23.39$, $p < 0.05$) and between all three levels of WM Load (two-items versus four-items, $F(1,43) = 37.52$, $p < 0.05$; two-items versus distractors-present, $F(1,43) = 17.80$, $p < 0.05$; four-items versus distractors-present, $F(1,43) = 9.56$, $p < 0.05$). Means showed that RT decreases with increased cue constriction and with decreased WM Load (see Table 1).

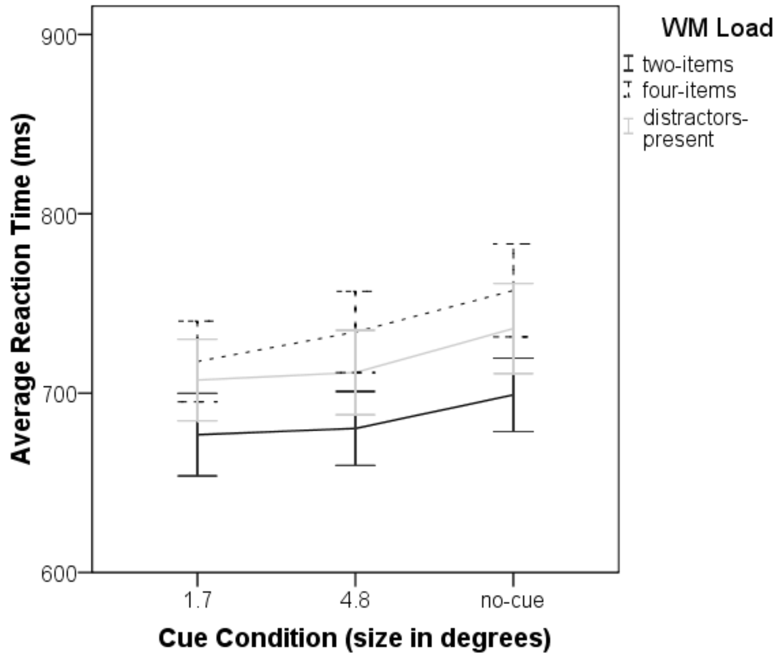


Figure 15. Decision RT as a function of Cue Condition and WM Load

Table 1. RT means

	Mean	***Standard Deviation***
Cue Condition		
No-cue	733.46	21.80
1.7°	703.12	20.67
4.8°	711.30	20.03
WM Load		
Two-items	687.89	19.46
Distractor	721.10	21.80
Four-items	738.89	22.00

Accuracy

An omnibus 3 (WM Load) by 3 (Cue Condition) ANOVA was conducted on accuracy with WMC as a between-subjects variable. Results showed significant main effects of WM Load ($F(2,84) = 28.79$, $p < 0.01$, $\eta^2 = 0.38$) and Cue Condition ($F(2,84) = 22.63$, $p < 0.01$, $\eta^2 = 0.32$) and a significant interaction between Cue Condition and WM Load ($F(4,168) = 5.55$, $p < 0.01$, $\eta^2 = 0.15$; See Figure 16). The between-subjects effect of group was also significant ($F(1,42) = 7.44$, $p < 0.01$, $\eta^2 = 0.15$), such that accuracy was higher for the high-WMC group (low-WMC, M = 0.76, SD +/- 0.02; high-WMC, M = 0.84, SD = 0.02). Pairwise comparisons were then conducted using a Bonferroni correction. These analyses showed only significant differences between the no-cue condition and the 1.7° and 4.8° cue (no-cue versus 1.7°, $F(1,43) = 28.32$, $p < 0.05$; no-cue versus 4.8°, $F(1,43) = 25.79$, $p < 0.05$) and between all levels of WM Load (two-items versus four-items, $F(1,43) = 56.94$, $p < 0.05$; two-items versus distractors-present, $F(1,43) = 15.34$, $p < 0.05$; four-items versus distractors-present, $F(1,43) = 15.51$, $p < 0.05$). The means revealed that accuracy was lowest under the no-cue condition compared to the 1.7° and 4.8° cue conditions (see Table 2). Additionally, accuracy was best when WM Load was two-items and worst when WM Load was four-items, with the distractors-present condition having an accuracy level between the other two levels of WM Load (see Table 2).

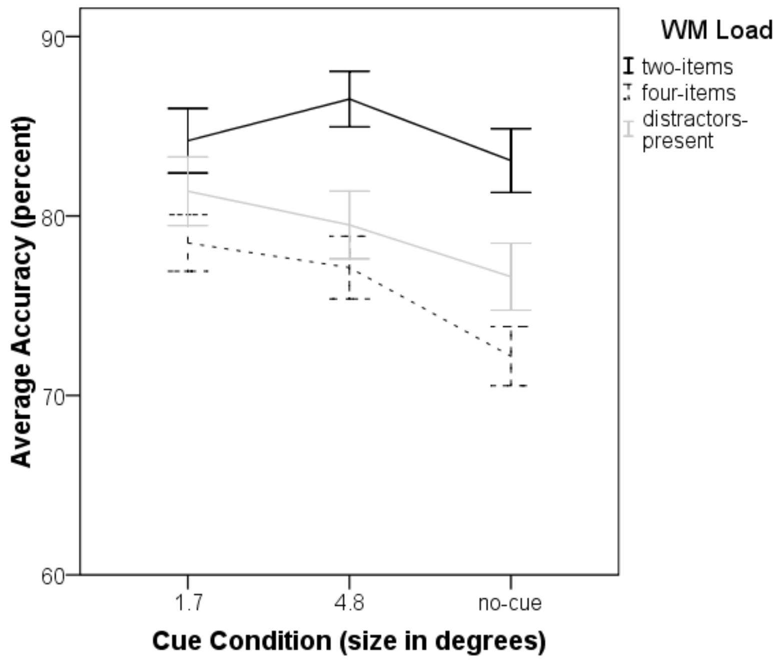


Figure 16. Accuracy plotted as a function of Cue Condition and WM Load

Table 2. Accuracy means

	Mean	*Standard Deviation*
Cue Condition		
No-cue	0.77	0.01
1.7°	0.81	0.02
4.8°	0.81	0.02
WM Load		
Two-items	0.84	0.02
Distractor	0.76	0.01
Four-items	0.79	0.02

Based on the significant between subjects effect of WMC, a 3 (WM Load) by 3 (Cue Condition) ANOVA was conducted on accuracy for each WMC group separately.

For the low-WMC group there were significant main effects of Cue Condition and WM Load (Cue Condition, $F(2,40) = 16.67$, $p < 0.01$, $\eta^2 = 0.46$; WM Load, $F(2,40) = 13.90$, $p < 0.01$, $\eta^2 = 0.41$) as well as a significant interaction between Cue Condition and WM Load ($F(4,80) = 3.74$, $p < 0.01$, $\eta^2 = 0.16$). Pairwise comparisons with Bonferroni corrections showed significant differences between the no-cue condition and all cue sizes (no-cue versus 1.7°, $F(1,20) = 23.99$, $p < 0.05$; no-cue versus 4.8°, $F(1,20) = 18.40$, $p < 0.05$) such that accuracy increased with the presence of cues (Mean difference for 1.7° cue = −0.06; Mean difference for 4.8° cue = −0.05). Additionally, there were significant differences between the four-items WM Load condition and all other WM Load conditions (four-items versus two-items, $F(1,20) = 22.15$, $p < 0.05$; four-items versus distractors-present, $F(1,20) = 10.05$, $p < 0.05$) such that accuracy was lowest under four-items WM Load conditions and best under two-items conditions.

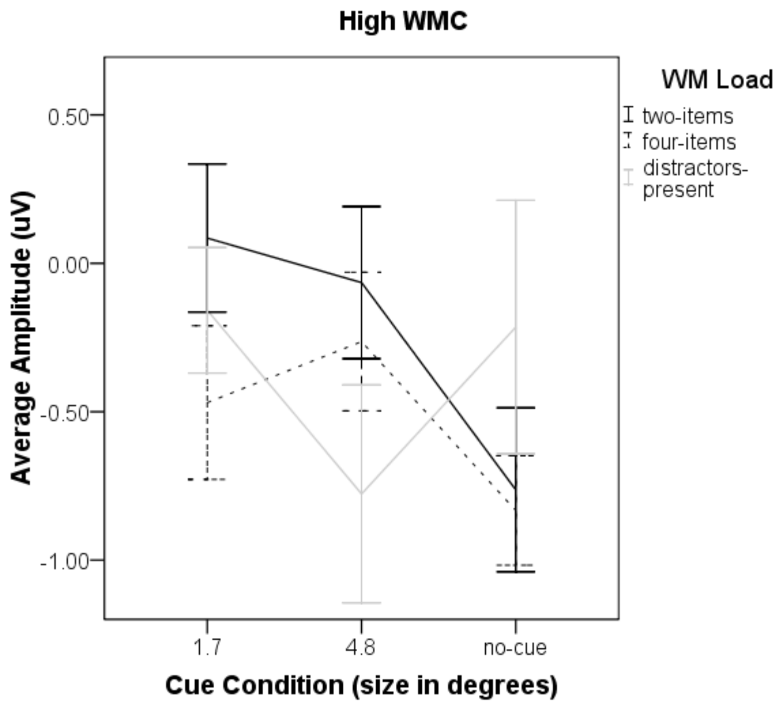
For the high-WMC group there were significant main effects of Cue Condition and WM Load (Cue Condition, $F(2,44) = 6.33$, $p < 0.05$, $\eta^2 = 0.22$; WM Load, $F(2,44) = 14.86$, $p < 0.01$, $\eta^2 = 0.40$) but no significant interaction. Pairwise comparisons with Bonferroni corrections showed significant differences between the no-cue condition and the 4.8° condition ($F(1,22) = 18.40$, $p < 0.05$), such that performance improved with cue presence (Mean difference between no-cue and 1.7° cue = −0.03; Mean difference for between no-cue and 4.8° cue = −0.03). Additionally, there was a significant difference between the two-items condition and the four-items condition ($F(1,22) = 20.68$, $p < 0.05$), such that performance was best for the two-items WM Load condition (two-items, $M = 0.88$, $SD = 0.02$; four-items, $M = 0.80$, $SD = 0.02$).

FILTER TASK (BRAIN WAVE)

Baseline correction and filtering was applied to ERP epochs from −100ms to 1000ms, with the baseline beginning 100ms prior to delay period onset. In accord with the analysis procedure used in the study on which this experiment was based (Vogel, *et al.*, 2005), statistical analyses were conducted on the ERP data from electrode sites P3 and P4. Data from these electrodes was used for the calculations of the difference waves (CDA) and of filtering efficiency, which is based on the CDA. The CDA was calculated by subtracting ipsilateral from contralateral voltage (McCollough, *et al.*, 2007) between 300–900ms following delay period onset and then averaging those subtractions. The formula for filtering efficiency, following that used by Vogel, *et al.*, 2005, was as follows: $(F - D) / (F - T)$, where F is the averaged CDA amplitude when four stimuli are present, D is the CDA amplitude when two distractors and two targets are present, and T is the CDA amplitude when two targets are present.

CDA Analyses

An omnibus 3 (Cue Condition) by 3 (WM Load) ANOVA was conducted on the CDA voltage averaged over 300–900ms with WMC Group as a between subjects variable). Results revealed significant main effects of Cue Condition ($F(2,84) = 7.94$, $p < 0.01$, $\eta^2 = 0.16$) and WM Load ($F(2,84) = 5.26$, $p < 0.05$, $\eta^2 = 0.11$; see Figure 17). No other effects were significant. Pairwise comparisons with Bonferroni corrections were also performed in order to determine the direction of the significant main effects. These comparisons show that when levels of Cue Condition were compared collapsed across all other factors a significant difference between the no-cue and the 1.7° cue conditions ($F(1,43) = 15.42$, $p < 0.01$) such that under the no-cue condition, CDA amplitude was lower than under the 1.7° cue condition (no-cue, 1.7° = −0.62, SE = 0.15). There was also a significant difference between the two-item and four-item levels of WM Load when collapsed across all other factors ($F(1,43) = 13.38$, $p < 0.05$), such that when WM Load was four-items, CDA amplitude was more negative than when WM Load is two-items (two-items − four-items = −0.10, SE = 0.11).



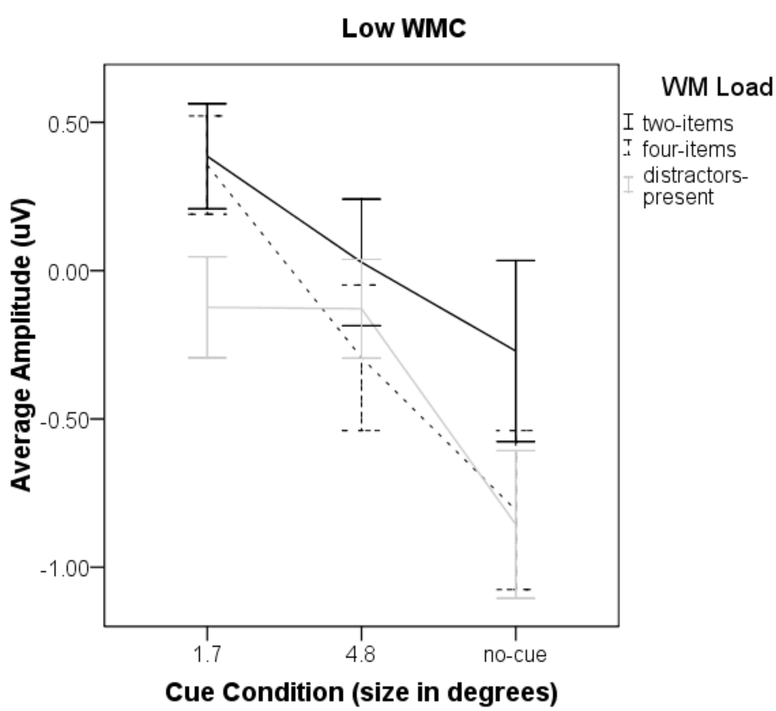


Figure 17. Averaged CDA plotted as a function of Condition and WM Load
(Top graph is high-WMC group and bottom graph is low-WMC group)

Filtering Efficiency Analysis

In accord with the procedure of the study on which this paradigm was based (Vogel, *et al.*, 2005), analyses were also performed on filtering efficiency (calculation on CDA described above). It is important to note that the data from three participants had to be excluded due to filtering efficiency results that were at least three standard deviations above or below the mean. Following Vogel, *et al.* (2005), the first step correlated filtering efficiency with WMC for each person for each Cue Condition. WMC was significantly correlated with filtering efficiency under no-cue and 1.7° cue conditions (no-cue, $r = 0.32$, $p < 0.01$; 1.7°, $r^2 = -0.26$, $p < 0.05$), but not under the 4.8° cue condition ($p > 0.05$; see Figure 18). Interestingly, the direction of the significant correlation between filtering efficiency and WMC was dependent on the level of Cue Condition. Under the no-cue condition, there was a positive correlation, indicating that as WMC increased so did the ratio of the filtering efficiency calculation, whereas under the 1.7° cue condition, the correlation was negative, suggesting the opposite.

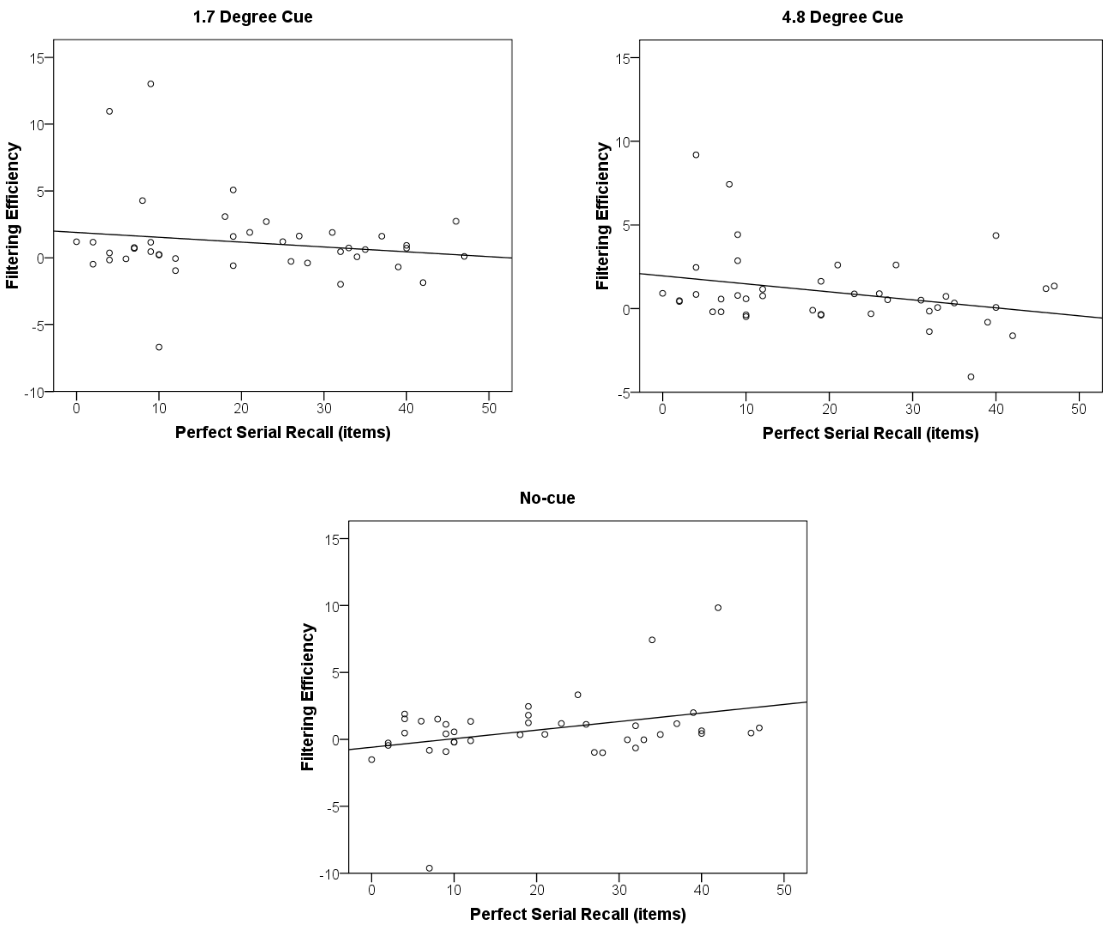


Figure 18. Correlation of Perfect Serial Recall with Filtering Efficiency
(Top is 1.7° cue, middle is 4.8° cue, and bottom is no-cue)

When the measure of filtering efficiency was derived it was intended to only account for values between 0 and 1, with 1 representing identical performance between low-WMC conditions and those with distractors-present. However, this study yielded cases with filtering efficiencies both above and below this range, suggesting that further analyses would be useful for interpretation of the significant correlations to provide insight into the previously discussed correlations between WMC and filtering efficiency. In an exploratory analysis, both the top (the CDA amplitude averaged over 300–900ms for the four-items condition minus the CDA amplitude averaged over 300–900ms for the distractors-present condition) and bottom portions (the CDA amplitude averaged over 300–900ms for the four-items condition minus the CDA amplitude averaged over 300–900ms for the two-items condition) of the filtering efficiency equation were next individually correlated with WMC to further explore the correlations between WMC and filtering efficiency in all cue conditions.

The results showed a significant correlation with WMC under 1.7° cue conditions when the averaged CDA amplitude from the four-items WM Load condition was subtracted from the distractors-present WM Load condition ($r = -0.35$, $p < 0.05$). The correlation was not significant when the CDA amplitude in the four-items WM Load condition was subtracted from the two-items WM Load condition. The correlation between WMC and the difference between averaged CDA amplitude in the four-items WM Load condition and the distractors-present WM Load condition was negative, such that as the difference in CDA amplitude between the conditions increases, WMC decreases. This suggests that those with low-WMC were more likely to have positive subtraction values while those with high-WMC were more likely to have negative subtraction values. This implies that when pre-cues were 1.7° and VA presumably constricted, those with high-WMC showed a more positive CDA amplitude, closer to that in the two-items condition, when distractors were present, while those with low-WMC showed a more positive CDA amplitude, that was closer to that in the two-items condition, when WM Load was four-items without distractors. This conclusion is supported by the waveform graphs (see Figures 19, 20, and 21). These correlations can also be interpreted as suggesting that high-WMC group experienced the least load under the distractors-present condition while the low-WMC group experienced the least load under the two-targets condition.

Under the no-cue condition, although there was a significant correlation between filtering efficiency and WMC there were no significant correlations between the subtractions that made up the filtering efficiency calculation and WMC. This suggests that it was the ratio between the subtractions that resulted in the observed significant correlation between filtering efficiency and WMC. Thus, this correlation can be interpreted as suggesting that as filtering efficiency increased so did WMC.

While there was no significant correlation between the filtering efficiency calculation as a whole and the 4.8° cue the follow up correlations were conducted to ensure that the reason was a lack of a relationship between the CDA amplitudes for each Cue Condition between WMC groups. These follow up analyses revealed no significant correlations between the subtractions that compose the filtering efficiency calculation and WMC. Given that the correlation between filtering efficiency and WMC was also non-significant this suggests that there is no difference between WMC groups regarding their ability to exclude distracting information. To further solidify this conclusion WMC was also correlated with the result of subtracting the CDA amplitude averaged over 300–900ms for the distractors-present condition minus the CDA amplitude averaged over 300–900ms for the two-items condition when the 4.8° cue was used. The result of the correlation was non-significant. This supports the aforementioned conclusion that when the 4.8° cue is used there is no relationship between WMC and filtering efficiency by suggesting that CDA amplitude of all WM Load conditions are not significantly different.

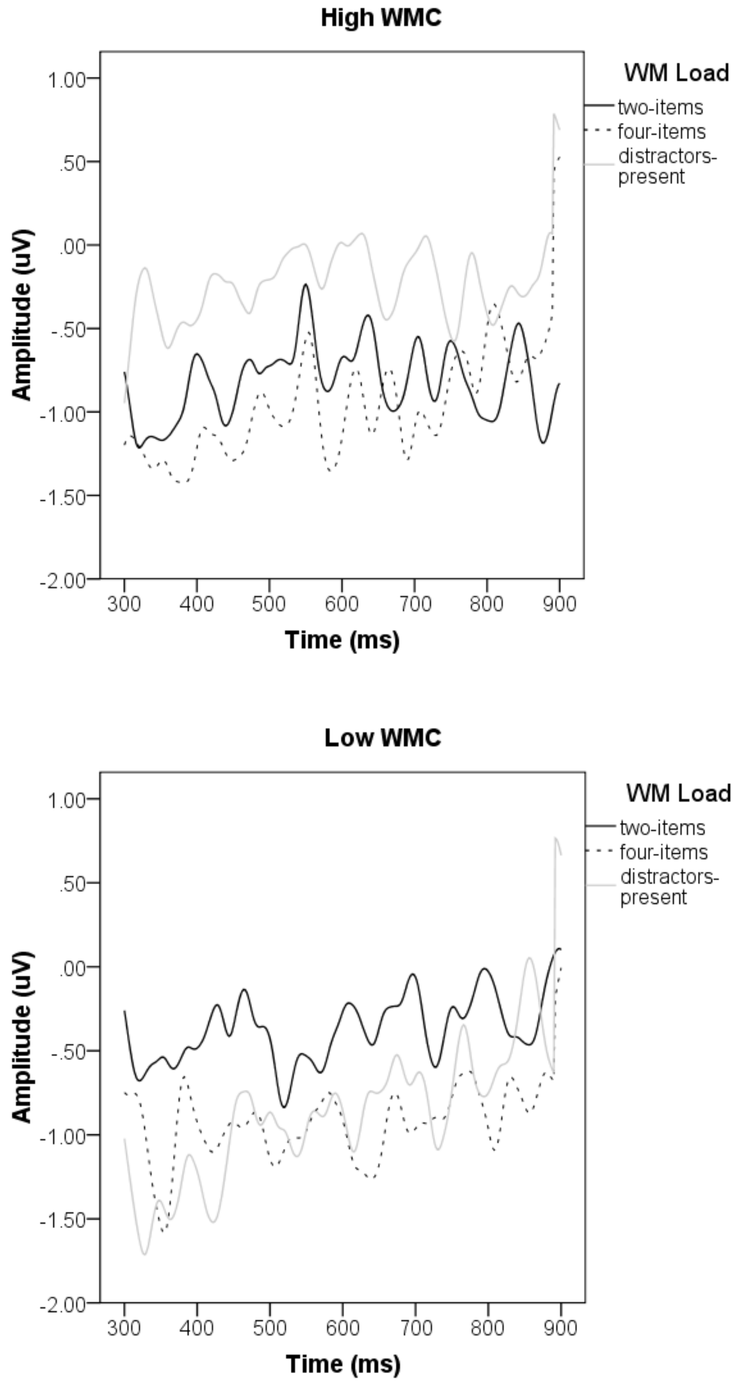


Figure 19. CDA waveform graph during no-cue trials
(High-WMC group at top and low-WMC group at bottom)

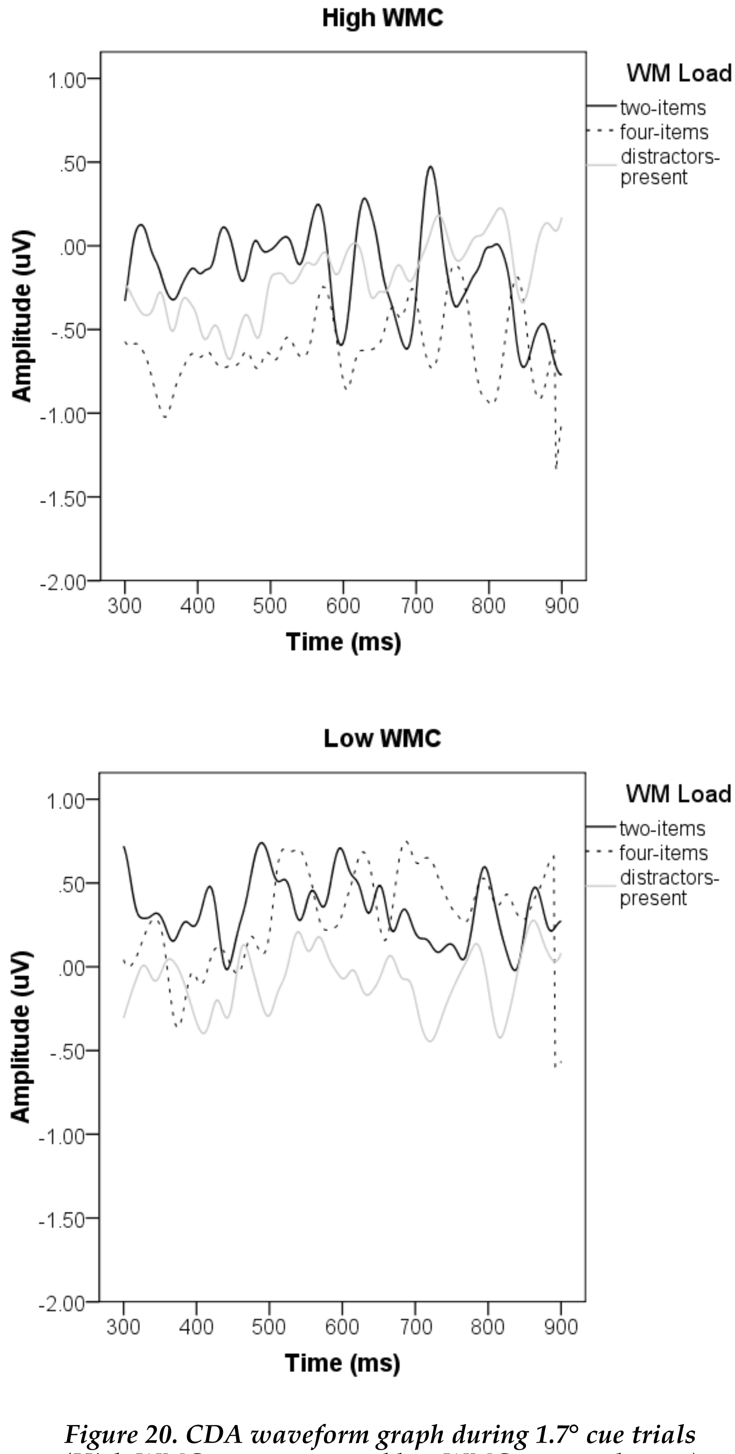


Figure 20. CDA waveform graph during 1.7° cue trials
(High-WMC group at top and low-WMC group at bottom)

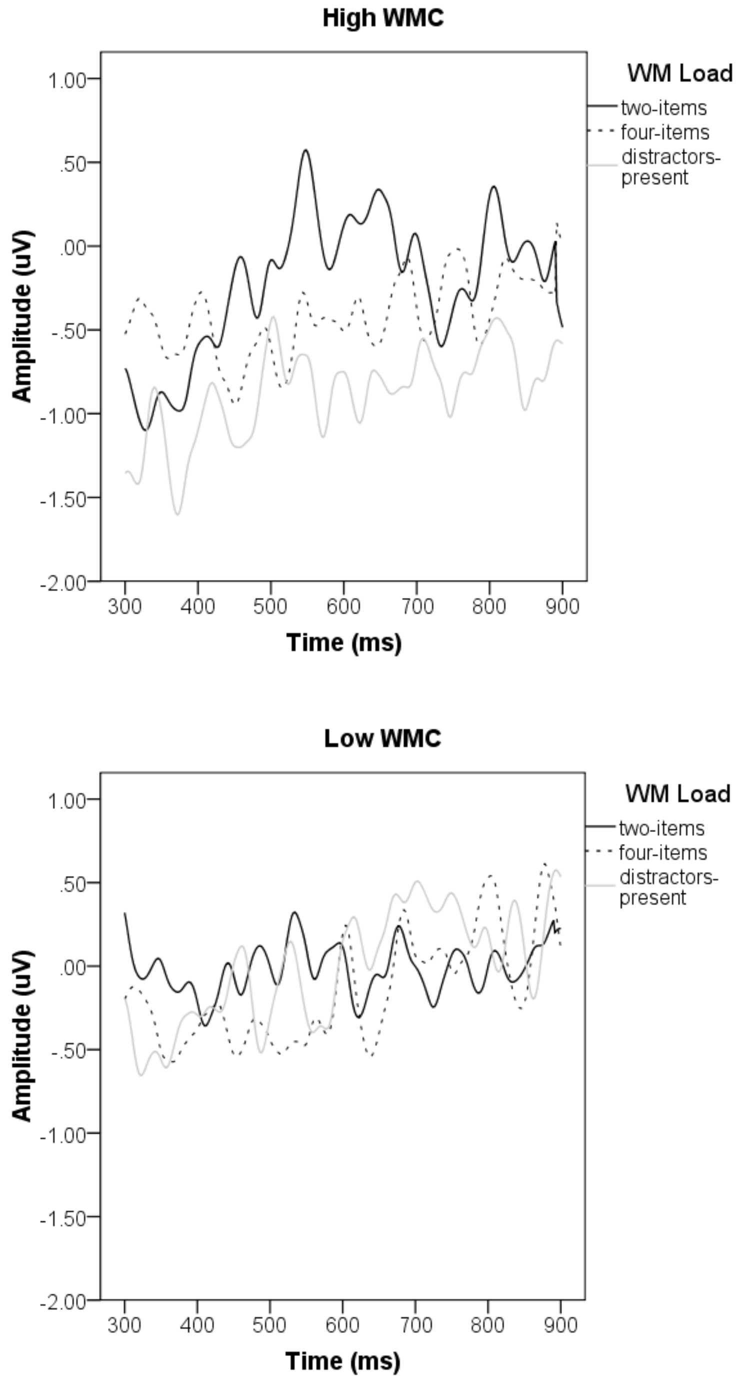


Figure 21. CDA waveform graph during 4.8° cue trials
(High-WMC group at top and low-WMC group at bottom)

Raw Frontal EEG Analysis

In an effort to demonstrate the strength of the experimental findings of this study, we also attempted to find support for previously established phenomena. Specifically, a previous study has shown that contralateral positivity from frontal electrode sites observed during the retention interval (averaged 300–900ms) of a WM task was sensitive to attentional manipulations, but not to the increased constriction of attention (Clarke, *et al.*, 2010). We tested whether or not this was the case in the present study, using a repeated measures ANOVA on the raw contralateral positivity (averaged across 300–900ms interval) at contralateral frontal electrodes F3 and F4 with Cue Condition, WM Load, and hemisphere (contralateral F3, contralateral F4) as within subjects factors. There were significant main effects of Cue Condition ($F(2,41) = 10.42$, $p < 0.01$, $\eta^2 = 0.24$) and WM Load ($F(2,41) = 10.96$, $p < 0.01$, $\eta^2 = 0.21$) as well as a significant interaction between Cue Condition and WM Load (see Figure 22). We then removed the no-cue condition and repeated the analysis (i.e. a 2 (Cue Size) by 3 (WM Load) by 2 (hemisphere) ANOVA on raw averaged CDA amplitude). The results of this analysis only showed a significant effect of WM Load ($F(2,41) = 8.03$, $p < 0.01$, $\eta^2 = 0.16$)

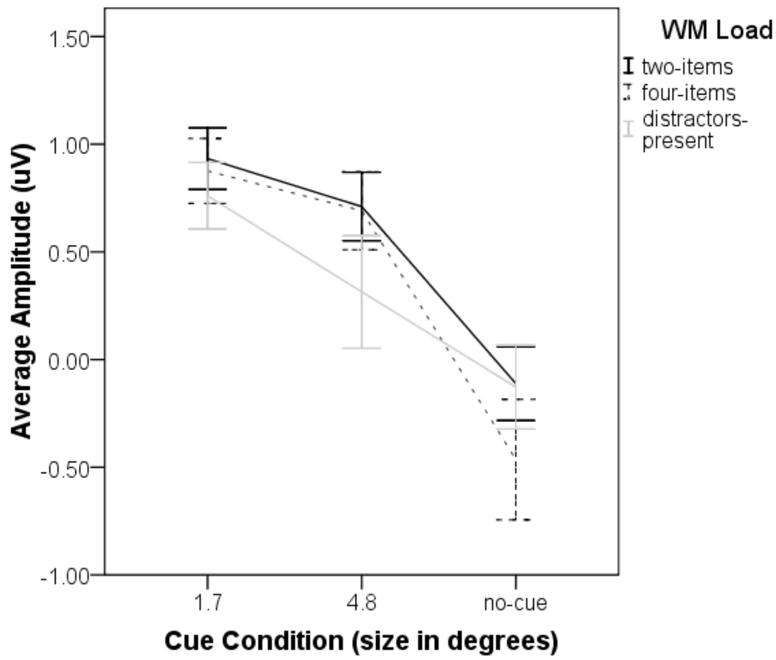


Figure 22. Graph of Cue Size by WM Load effect on raw CDA amplitude at frontal electrodes

Discussion

Experiment 3 sought evidence in support of the hypothesis that a new process forms when WM and VA are deployed simultaneously. The paradigm used to test the hypothesis in this study was selected based on previous evidence that high- and low-WMC individuals differed in their ability to exclude distracting information from processing in WM (Vogel, *et al.*, 2005). Experiment 3 modified that design by manipulating pre-cue size in order to determine whether the scale of VA induced a change in distractor suppression during WM maintenance. The integrated view predicted that increased attentional constriction would result in the enhanced ability to exclude distracting information, leading to increased CDA similarity between high- and low-WMC individuals. The parallel view predicted instead that while the use of pre-cues should result in enhanced filtering efficiency, that efficiency would not be affected by increased constriction of the pre-cue. The results from this study supported the integrated view in that the manipulation of VA resulted in graded effects on WM, suggesting that the two processes were sharing resources.

There was strong evidence supporting the conclusion that the relationship between WMC and filtering efficiency was modulated by Cue Condition. Based on the filtering efficiency analysis, those with low-WMC were less able to filter out distracting information than those with high-WMC when there was no attentional pre-cue. When a 1.7° pre-cue was used, there was still a relationship between filtering efficiency and WMC, but its effect differed depending on WMC group. For those with low-WMC the CDA amplitude of the four-items condition was similar to that in the two-items condition but not to the distractors-present condition. This suggests that the cue increased their ability to encode targets, but did not effect distractor suppression. The high-WMC group showed the opposite effect, the use of the 1.7° pre-cue resulted in the CDA amplitude of the distractors-present condition being similar to that in the two items-condition but not to the four-items condition. This implies that the cue increased their ability to suppress distractors, but not to encode targets. When the 4.8° pre-cue was used, there was no association between WMC and filtering efficiency or with any of the relationships between WM Load, suggesting that following a larger pre-cue, those with high-WMC performed similarly to those with low-WMC. These results support the integrated view, which predicted that the manipulation of Cue Condition would result in differences in the filtering efficiency of low-WMC individuals.

It was predicted that greater cue constriction would result in an increased ability to filter out distracting information. However, it was instead observed that the larger 4.8° cue resulted in optimal filtering performance. This is consistent with our previous finding (Greenwood, Lambert, Sunderland, & Parasuraman, 2005) that in a WM task, a cue which encompassed a portion of the background information, represented by the 4.8° cue in this experiment, often leads to better performance when compared to a cue that surrounds only the target, as did our 1.7° cue.

One of the most interesting results from the analyses of filtering efficiency and Cue Condition was the source of the correlation between filtering efficiency and WMC when the 1.7° pre-cue was used. Under the 1.7° pre-cue condition, the correlation between filtering efficiency and WMC was due to differing relationships between the CDA amplitudes of the levels of WM Load as a function of WMC group. Specifically, those with lower WMC had a more negative CDA under the distractors-present compared with the two-items condition, such that the CDA amplitude of the four-items condition was similar to that of the two-items condition. This suggests that the 1.7° cue aided the ability of those with low-WMC scores to encode and maintain targets, but not affect their ability to exclude distracting information. Those with high-WMC scores showed the opposite pattern—a more negative CDA in the four-items WM Load condition compared to the distractors-present condition, such that the CDA amplitude of the distractors-present condition was similar to that of the two-items condition. The latter finding suggests that those with high-WMC found 4 targets to be a greater load than 2 targets and 2 distractors, consistent with Vogel *et al*. (2005). This suggests that the 1.7° cue helped this group to exclude distracting information, but did not aid in the processing of the four-items WM Load target stimuli. These results suggest that the optimal degree of attentional constriction during a WM task is dependent upon the participant's WMC and the nature of the task. When distractors are present, low-WMC individuals benefit most from a cue that encompasses some background information, while if there are no distractors, a cue that encompasses just the target is optimal. For those with high-WMC, a cue of either size is sufficient to improve performance regardless of whether or not distractors are present.

Results from this study also show support for previously observed phenomena. It was found that behavioral performance was optimal when WM Load was two-items and the pre-cue encompassed both the target and some background. Also, there was a difference between the filtering efficiency of low- and high-WMC individuals under no-cue conditions and a difference in the CDA amplitude between WMC groups. Additionally, the amplitude of the frontal EEG waveforms was modulated by manipulations in VA, as has been demonstrated in previous studies (Clarke, *et al.*, 2010). Thus, several previously established phenomena related to WM and VA were observed in this study.

Overall, results of the third experiment supported the integrated view, which predicted that pre-cue size would modulate the neurophysiological manifestations of WM maintenance processes. The alternative parallel view predicted a difference in the association between the neurophysiological data and WMC when a pre-cue was used versus when it was not, but no effect on the CDA of increased attentional constriction related to WMC. The results supported the integrated view by showing that the manipulation in VA resulted in graded changes in the process of WM. Specifically, the use of different sized cues resulted in fundamentally different relationships between WM and filtering efficiency as a function of WMC.

5. GENERAL DISCUSSION

This dissertation explored the nature of the relationship between WM and VA. Based on previous findings suggesting a link between WM and VA, we hypothesized that when these two processes are simultaneously deployed, they become integrated to form a new process. This hypothesis was termed the integrated view and, in this dissertation, was compared to a specific alternative hypothesis. Given the substantial previous literature demonstrating interactions of some kind between WM and VA, the appropriate alternative hypothesis was that these processes remain independent processes that are highly interactive. This alternative hypothesis is referred to as the parallel view. Three experiments, each focused on a specific aspect of the WM and VA relationship, were conducted to test this hypothesis. These experiments used both behavioral and electrophysiological metrics of performance. In support of our hypothesis, all three experiments provided converging evidence for the integrated view.

There is a wealth of previous literature indicating a close relationship between WM and VA from a variety of measurement techniques—from behavioral to neurophysiological to genetic. For example, fMRI studies have shown that while WM and VA activate non-overlapping areas of the brain, areas of co-activation also exist (LaBar & Gitelman, 1999). Additionally, studies using molecular genetics show both separate and overlapping effects of neurotransmission systems. Specifically, normal variation in a dopaminergic gene (DBH) was selectively associated with WM performance, variation in a nicotinic cholinergic gene (CHRNA4) was selectively associated with attention (Greenwood, Fossella, & Parasuraman, 2005; Parasuraman, Greenwood, Kumar, & Fossella, 2005), but both genes affected performance when VA was manipulated in a WM task (Greenwood, Lin, Sundararajan, Fryxell, & Parasuraman, 2009). Such previous work provides strong evidence of the existence of a relationship between WM and VA, but does not explain how the processes are related and could also suggest that the two processes are simply additive when simultaneously deployed.

Evidence from the three experiments converged to support the integrated view—that WM and VA form a new process when simultaneously deployed. Specifically, behavioral evidence revealed that the manipulation of WM load modulated effect of the timing of attentional deployment (Experiment 1) and the manner in which visuospatial attention is distributed in space (Experiment 2). Electrophysiological measures provided evidence that VA affected the ability of low-WMC individuals to exclude distracting information from WM maintenance. Considered together, we interpret these findings as consistent with the idea that when WM and VA are simultaneously deployed they share processing resources, indicating that they no longer operate as independent processes. Given that (a) each experiment probed a different aspect of the relationship between WM and VA, and (b) multiple metrics of performance were obtained, the results can be interpreted as providing strong converging evidence in support of the hypothesis.

Each experiment also replicated previously reported effects of each process. Consistent with well-established phenomena, performance was enhanced when targets were the focus of VA and impaired when WM load was increased. Additionally, an attentional distribution with a suppressive annulus surrounding an area of enhanced processing was found under certain conditions (e.g., Muller, Mollenhauer, Rosler, & Kleinschmidt, 2005). Finally, when WM load was low, the timing of attentional deployment did not result in differences in behavioral performance on a WM task (consistent with Griffin & Nobre, 2003). The replication of previous findings lends credence to the novel findings of these experiments. The present findings have broad ramifications for the field of WM. If the findings are replicated, current models of the relation between WM and VA will need to account for the present findings.

Evidence in Support of Attention–Memory Integration

The behavioral findings from each study, as well as previous evidence, provide specific evidence bearing on the hypothesis that WM and VA form a new process when simultaneously deployed. In what follows, results of each experiment are examined and discussed in the context of the hypothesis.

EXPERIMENTAL FINDINGS SUPPORTING INTEGRATED VIEW

Experiment 1 was designed to test the integrated hypothesis by examining whether a manipulation in WM would modulate the effects of VA on WM task performance. Behavioral evidence from this study indicated that the effect of VA was not restricted to the stage of processing during which it was deployed and instead the effects persisted throughout subsequent phases. Specifically, performance was enhanced when VA was deployed either prior to (pre-cue) or both prior to and following (both-cues) the presentation of the target compared to when VA was deployed only prior to the presentation of the target (post-cue). However, this effect was only observed behaviorally when WM load was high. This was taken as evidence that WM and VA share processing resources, such that VA was able to compensate for insufficient WM resources. This demonstration of resource sharing between WM and VA is consistent with the hypothesis that they integrated to form a new process. Additionally, under high WM load, the post-cue condition resulted in worse performance than under the no-cue condition when VA was not deployed at all. In contrast, performance was enhanced under the both-cues condition (post-cue in combination with a pre-cue). Deploying VA prior to target presentation appeared to counteract the apparently disruptive effect of the post-cue. While the use of VA led to the formation of the new integrated process by WM and VA, the post-cue led to diminished performance perhaps because it was deployed after the target has been encoded in WM and maintenance had begun, thus interrupting these processes. However, if the pre-cue was deployed prior to the post-cue, the mental representation may have been formed before the post-cue was presented. There is some evidence that by the stage of WM maintenance, the mental representation has become an integrated object (Astle, *et al.* 2009). Evidence from Experiment 1 suggests that pre-cues somehow facilitate that process so that following a pre-cue, the mental representation is less vulnerable to interference by the post-cue. In the absence of a pre-cue, the post-cue does disrupt performance, presumably by interfering in some way with the mental representation.

Experiment 2 examined the effect of WM load on the distribution of VA in space. According to the integrated view, when VA and WM are deployed in the same task, changes in one process should fundamentally change the other due to shared resources. Thus, the integrated view predicted that increased WM load would change the distribution of visuospatial attention. The parallel view is that the two processes can influence each other, but cannot lead to graded changes within each other as they do not share resources, and so predicts only an increase or decline in the efficiency of processing within the attentional focus without an accompanying change in the distribution of VA. The results of the study revealed that the attentional distribution was altered by a modulation in WM load. Specifically, when load was low, evidence of a suppressive annulus surrounding the focus of attention was found, while at high load, the distribution of attention was distributed broadly. Originally, we predicted that the suppressive annulus would be observed under both low and high WM load conditions, but would be more concentrated at the center of the focus on higher load trials. Evidence for this was not found; instead a suppressive annulus was seen surrounding a central area of enhanced processing under low load, but not under high WM load. However, the lack of a suppressive annulus surrounding the attentional focus under high load does not alter the conclusion that the integrated view was supported and instead provides valuable insight into when a suppressive annulus in the attentional distribution is induced (Cutzu & Tsotsos, 2003).

We speculate that the shape of the distribution is modified as a function of available resources. Specifically, under low WM load the shared resources of the process formed by WM were not strongly taxed and so VA could be optimally distributed, including with a suppressive annulus. However, under high WM load the shared resources were more strongly taxed so that they were less available for the formation of the optimal attentional distribution.

Experiment 3 examined the effect of attentional constriction on the ability of individuals to filter distracting information. Here electrophysiological data allowed for an examination of the relationship between filtering efficiency (an EEG derived neurophysiological measure of ability to exclude distracting information), WMC, and attentional constriction. Previous work had shown that intra-individual differences WMC were associated with filtering efficiency, such that low-WMC individuals were less able to prohibit the processing of distracting information (Vogel, *et al.*, 2005). The integrated view predicted that the operation of the integrated process on shared resources would result in increased attentional constriction improving the filtering efficiency of low-WMC individuals. The parallel view predicted that the use of VA would reduce the difference in filtering efficiency between high- and low-WMC individuals, but that increased attentional constriction via manipulation of pre-cue size would not produce any additional benefits. Results provided support for the integrated view, in that the relationship between filtering efficiency and WMC differed depending on the degree of attentional constriction.

These results suggest a sharing of resources between WM and VA. Specifically, because WM and VA are integrated into a new process the lack of WM resources can be overcome due to the availability of VA resources attributed to the suppression of irrelevant information. Thus, the difference between those with low and high-WMC is the functioning efficiency of the integrated process formed by WM and VA

While Experiment 3 did provide support for the integrated view the change in the relationship between WMC and filtering efficiency as a function of attentional constriction was not as was originally predicted. The optimal cue size for filtering out distracting information for those with low-WMC was the larger cue, not the smaller cue. This can be interpreted in the context of previous work showing that the optimal cue size varies with the task (Greenwood, *et al.*, 2005). Further, when the small cue was used there was an unexpected difference in its benefit to processing between WMC groups. The use of the small cue resulted in an enhanced ability to encode targets by those with low-WMC, but it did not aid suppression of distracting information. For those with high-WMC, the small cue helped to suppress distracting information, but not to encode the targets. This suggests that WM and VA share physiological processing resources when simultaneously deployed, as predicted by the integrated view, and that those with high and low-WMC use these resources differently.

The involvement of VA in filtering efficiency, or the suppression of distracting information, is supported by previous research. Super *et al.* (2001) observed that, during the presentation of a figure-ground stimulus, there was enhanced firing to the figure and suppressed activity to the ground in a brain area associated with VA, the posterior cortex. Further, Serences, Yantis, Culberson, and Awh (2004) showed the suppression of distractors were associated with activity in a specific area of visual cortex.

PREVIOUS LITERATURE SUPPORTING EXPERIMENTAL FINDINGS

Our finding that WM and VA can form a new process is novel, but is also consistent with previous literature—including behavioral and neurophysiological studies, as well as theoretical propositions—that has indicated the potential for WM and VA to form a new process.

The sharing of resources between WM and VA has been demonstrated in previous literature. Specifically, Oh and Kim (2004) had participants perform a visual search task within either a spatial or nonspatial WM task. The visual search task required participants to indicate whether or not an upright, L-shaped figure was present in an array of L-shaped figures of varying orientation. In the spatial WM task, participants memorized the locations of four black squares and were asked to indicate if a probe presented later was in the same location of any of the previously memorized squares. In the nonspatial WM task, stimuli were multi-colored squares, and participants were asked to memorize the colors of the squares. The visual search task was performed during the delay period of the spatial or nonspatial WM task. They found that the visual search task interfered with a spatial working memory load, but not a nonspatial working memory load. This was taken to suggest that spatial and nonspatial working memory can be separated by their interaction with visual search tasks, such that visual search and spatial working memory storage require the same capacity mechanisms. By extension, visual search and nonspatial working memory storage appear not to share storage capacity. Given that visual search tasks are associated with VA, these results suggest a sharing of resources between spatial WM and VA, as would be expected if the two formed an integrated process. In all three of the studies this dissertation we found evidence of an integrated process that depends upon the hypothetical shared resources of WM and VA. However, this study also indicates that our integrated hypothesis may be most relevant to the relation between VA and specifically spatial WM.

Evidence that VA is associated with feature binding in visual WM storage (Fougnie & Marois, 2009) is also relevant to our findings. This was demonstrated in a study in which an attention-demanding task was performed during a visual WM task. The attention-demanding task was a multiple object tracking task (MOT). The visual WM task was a simple delayed-match-to-sample paradigm. In the visual WM task, participants either had to memorize the color, shape, color and/or shape, or color and shape of stimuli. Participants responded to the MOT task after the delayed-match-to-sample task. It was found that the effect of the MOT task on the delayed-match-to-sample task was largest when participants had to remember both the color and the shape of the stimuli. When a static MOT task was used, this effect remained, suggesting that it is not attributable to non-attentional factors. Further, when the visual WM task stimuli were presented sequentially—as opposed to concurrently—the aforementioned effect of the MOT task on the delayed-match-to-sample task when both color and shape was lessened. These results suggest that VA disrupts feature binding and maintenance in WM and led to the conclusion that VA is associated with feature binding in WM. This extends the claim of Treisman and Gelade (1980) that VA is necessary for the binding of features into object percepts. The extension of the role of VA in feature binding from perception through WM storage suggests a link between WM and VA through multiple stages of processing. This finding is consistent with the results of Experiment 1 in this dissertation, in which we demonstrated that the effects of VA propagate through multiple stages of WM processing. Thus, the results of the Fougnie and Marois (2009) study can also be interpreted as evidence that WM and VA can, and do, form an integrated process under certain conditions. Our findings go beyond those of Fougnie and Marois (2009) in showing that when the binding process is facilitated by attention, the percept is protected against interference.

The division of WM storage provides interesting insight into not only the potential of WM and VA to form an integrated process, but also into the necessary conditions to form that process. It has been found that there is a tripartite division of WM storage: iconic memory, fragile visual short-term memory, and visual WM (see Vandenbroucke, Sligte, & Lamme, 2011 for a review). The existence of iconic and visual WM has been known for some time while the presence of a third division is relatively recent. The reference of this new division as fragile visual short-term memory is proposed by Vandenbroucke et al. (2011). Iconic memory has a high capacity, but can only store items for a short period of time. Fragile visual short-term memory has a large capacity and can hold objects for multiple seconds, but can be easily overwritten. Finally, visual WM has a low capacity, but can hold items for a long period of time. Vandenbroucke et al. (2011) found, in a series of three studies, that visual WM and fragile visual short-term memory can be dissociated through their dependence on VA, such that decreasing VA greatly reduced visual WM, but only had a small effect on the capacity of fragile visual short-term memory. In all experiments in the series of studies by Vandenbroucke et al. (2011), a delayed-match-to-sample task with retro- or post-cues was used. Retro-cues were presented after the memory array, during the retention interval, and indicated which stimuli may change. In the post-cue trials, cues were administered simultaneously with the probe array. The difference in the timing of the deployment of VA between the retro-cue and post-cue trials allows for the measurement of fragile visual short-term memory and visual WM, respectively. In the first experiment, the uncertainty regarding the time that the relevant memory array would be presented was manipulated with additional cues. They found that performance suffered more with increased uncertainty during post-cue/visual WM trials than during retro-cue/fragile WM trials. This suggests that when attentional resources are not optimally engaged, visual WM suffers. In the second experiment they performed an n-back task to divert VA from the memory array and again found that when VA was diverted, performance on visual WM trials suffered more than performance on fragile WM trials. The third experiment used the uncertainty manipulation from the first experiment in an attentional blink paradigm. It was found that in visual WM trials, but not the fragile WM trials, performance to the stimuli in the secondary position suffered. Thus, all three experiments suggested a role for VA in visual WM, but not in fragile WM. When these results are combined with those from our studies, it suggests that the formation of the integrated process is dependent on the activation/use of the visual WM store. The integrated process may not be observed if iconic memory or fragile visual short term store is used instead of visual WM.

Not all studies draw conclusions that are consistent with the formation of the integrated process, but this may be due to failure to consider that possibility. Olivers and Eimer (2011) found that when observers not only stored a mental representation, but also had an expectation that it would appear, there was a stronger effect of distractors compared to when a mental representation alone was stored in WM. This implies that there attending to an item necessarily requires additional resources compared to storing an item. This was demonstrated by use of a paradigm that began with the presentation of a color to remember. In the first trial type, called "search-then-remember," participants were subsequently shown a stimuli array with no color, a color related to the memorized color, or an unrelated color and asked to search for a shape and respond to the letter inside. In the second trial type, called "remember-then-search," the task order was reversed. At the conclusion of both trial types, the participant was shown three colors and asked to indicate which matched their memorized color. When the search task was performed first they found that when distractors were similar to the memorized color, there was stronger interference than when they were not. This effect was not evident when the memory task was performed first. This was interpreted as indicating a stronger bias towards VA than WM, creating a functional dissociation between WM and VA. However, they failed to consider the possibility that their results could be attributed to an integrated process given that the trials with the attentional set used both WM and VA. It may be equally likely that the effect of the attentional set is actually the effect of the integrated process. An integrated process would be predicted to operate using the shared resources of WM and VA. This could result in a stronger bias towards trials during which the integrated process was used, as opposed to trials that simply used WM. The results from our studies support this alternative conclusion, but this could be further tested by comparing performance on a task that manipulates VA alone, WM alone, and both WM and VA.

The potential for WM and VA to form an integrated process is also supported by neurophysiogical evidence. Astle, et al. (2009) showed that the polarity of the ERP component N2pc was dependent on whether a feature search task was performed on a perceived or remembered array. They interpreted this finding as suggesting that once features enter WM, they become bound into objects, altering the level at which spatially-specific selection mechanisms must operate. Our results expand on this conclusion by suggesting that this spatially-specific selection mechanism is VA. Thus, it may be the formation of the new process between WM and VA that results in the opposite polarities, as the evaluation of a remembered array requires searching through the representation of that array held in WM while evaluating a perceived array does not require searching WM. Further, cognitive genetic work has shown that the neurochemical underpinnings of tasks involving WM and/or VA are different. WM and VA tasks are associated with unique neuromodulatory systems (Greenwood, Fossella, et al., 2005; Parasuraman, et al., 2005), while tasks that include both WM and VA are associated with an interaction between two sub-systems (Greenwood, et al., 2009). These findings suggest that WM and VA are separate processes, but interact in a very specific way, such that their interaction requires the support of multiple neuromodulatory sub-systems. Our findings imply that the interaction between multiple sub-systems is necessary to allow for the use of the shared resources of the new process formed between WM and VA.

Recently, a taxonomy of attention has been proposed (Chun & Golomb, 2011). At the most basic level, this taxonomy distinguishes between internal and external attention. External attention can be thought of as perceptual attention, while internal attention refers to the effects of attention on internally-generated information, such as goals. WM, although specifically assigned as a process on which internal attention acts, is proposed to be closest to the intersection between internal and external attention. This claim contributed significantly to the subsequent proposition that attention interfaces with WM to select relevant perceptions and actively maintain this information as internal representations (Chun & Golomb, 2011). These conclusions illustrate a dependency between WM and attention and, thus, VA, suggesting that there is the possibility that they could become integrated. This supports the finding of this dissertation that WM and VA form an integrated process from a theoretical perspective.

Together, past research has suggested a close relationship between WM and VA without being able to conclusively state the nature of this relationship. The studies in this dissertation were designed to make a more definitive conclusion regarding the nature of this relationship and found evidence that WM and VA form an integrated process when simultaneously deployed. The results of previous studies therefore not only support our experimental findings but also suggest that the integrated process may be constrained to spatial WM and the division of WM storage referred to as visual WM. Subsequent studies should examine whether the integrated process is restricted to scenarios which use spatial WM and visual WM storage.

Potential Mechanism for Shared Resources

While the studies in this dissertation provide evidence that WM and VA share processing resources when simultaneously deployed, suggesting that they have formed an integrated process, they do not allow for a conclusion regarding the exact nature of these resources. Determining the underlying neural mechanism associated with these shared resources is critical to the ability to make predictions regarding the effects of the integrated process. The results do, however, allow for speculation. We suggest that the shared resources may be dependent on the on an expanded version of the dorsal attention network (Corbetta, et al., 2008), such that it also includes the basal ganglia and prefrontal areas.

The dorsal attention network is activated by sustained attention to targets and suppressed by non-target events (Beauchamp et al., 2001; Corbetta, et al., 2008; Ozaki, 2011). The function of this network is to allow for the selection of sensory stimuli based on internal goals. Given that goal maintenance is a function of WM these characteristics suggest a relationship between this network and both VA and WM. Thus, it is an ideal candidate for the neural mechanism underlying the shared resources of the integrated process. Further, there is evidence that two core regions in the dorsal attention network, the frontal eye field and intraparietal sulcus, exert top-down influences on posterior storage areas (Bressler, Tang, Sylvester, Corbetta, *et al.,* 2008; Ozaki, 2011). The results of Experiment 3 (chapter 4) therefore support the dorsal attention network as a candidate mechanism for the shared resources of the integrated process in that both the constriction of attention around a target in a WM task and an increase in WM load were associated with a change in frontal and posterior CDA amplitude.

The typical dorsal attention network may need to be expanded to adequately account for the resources used by the integrated process. A previous study revealed that activity of the globus pallidus predicted the degree to which relevant information was stored in WM (McNab & Klingberg, 2007). Additionally, preceding activity in general prefrontal and basal ganglia areas were linked to inter-individual differences in WMC (McNab & Klingberg, 2007). Experiment 3 showed that VA modulated these differences. Together these results provide strong support for the role of the basal ganglia and prefrontal areas in the neural mechanism underlying the shared resources on which the integrated process operates.

Ramifications for the Field

Some of the findings of this dissertation are novel, with important implications for previously established views. Specifically, current views of the attentional distribution, the nature of the CDA, and theories of WM may need to accommodate the evidence obtained here of the integration of WM and VA into one process. Each is discussed in turn.

DISTRIBUTION OF ATTENTION

Observations of the attentional distribution have evolved as evidence has emerged. Most observations share the tenet that the attentional field decreases monotonically to zero with distance from the center of attention (Posner, *et al.*, 1980; Eriksen & St. James, 1986; Eriksen & Yeh, 1985; Downing, 1988). However, there is an increasing body of evidence that under certain conditions a region of apparent suppression can surround the attentional focus. The results of Experiment 2 (Chapter 3) provide an interesting insight into possible interpretations of data bearing on the shape of the attentional distribution. Experiment 2 revealed an area of enhanced processing surrounded by a region of suppression when WM load was low, but no such effect when WM load was high. Under high WM load, attention was broadly distributed without a focus. Thus, it appears that the attentional distribution is highly sensitive to WM load. As argued here, that is the result of WM and VA sharing resources consequent to formation of an integrated process. Specifically, the taxing of WM processing resources influenced the VA resources allocated to the attentional distribution in a graded manner, implying that these resources are being shared by an integrated process.

Interestingly, the region of suppression in low WM load conditions was only observable when RT data was used. If accuracy data was used the strength of perceptual facilitation afforded by attention decreased linearly with distance for the center of attention. Interestingly, RT data is typically used for VA tasks and accuracy data for WM tasks (Eriksen & St. James, 1986). Since WM and VA have formed an integrated process the difference is the attentional distributions demonstrated by these different measurement suggests that the actual shape of the attentional distribution is likely to be a hybrid of the two.

MODELS OF WM AND ATTENTION

Understanding of the nature of the process of WM and its relationship with attention has also evolved in the literature. Currently, the multicomponent (reviewed in Baddeley, 2007) and embedded processes (Cowan, 1999) views are widely accepted. The major difference between the two models is their view on the components of WM. The multicomponent model suggests that WM is composed of specialized sub-systems. The embedded processes model differs in postulating that WM is an emergent property. Both models are supported by evidence. Important for the present work, these models also differ in terms of the role assigned to attention. The embedded processes model gives much more responsibility to attention, assigning it the role of orchestrating WM processing. While both models carve out a large role for VA in the process of WM, neither makes predictions about the nature of this relationship. The results of this study suggest that the models should be amended to account for the formation of a new process when VA is deployed simultaneously with WM, such that performance on tasks during which VA and WM are deployed simultaneously is dependent on the resources shared between these two processes. Future models would also need to address the nature of these resources. The studies in this dissertation suggest that these resources include at least those involved in attentional distribution, target encoding, target maintenance, and suppression of distracting information. We speculate that this list of resources may include all those involved in an expanded version of the dorsal attention network (Corbetta, *et al.*, 2008). However, while it is likely that there are additional resources utilized in the new process their delineation will require future studies.

THE CDA

Several different research groups have observed that the amplitude of the CDA becomes more negative with increased WM load, reaching an asymptote at WMC (e.g., Vogel, *et al.*, 2004, McCollough, *et al.*, 2007). Our work has focused on the effect of VA on the CDA (Clarke, *et al.* 2010), observing that the CDA amplitude becomes increasingly positive with increased attentional constriction. Given that both WM and VA have been associated with modulations in the polarity of the CDA, but in opposing directions, we reasoned that the CDA was well-suited for studying the relationship between the two processes. The CDA was the basis for a measure designed to determine the ability of individuals to filter out distracting information (Vogel, *et al.*, 2005). Experiment 3 demonstrated that when attentional constriction was manipulated through the size of attentional pre-cues, the ability of individuals to filter out distracting information was modulated.

Future Directions and Limitations

The results of these experiments provide a solid foundation for the idea that WM and VA form an integrated process when simultaneously deployed. However, there are still aspects of this relationship to be explored, such as the exact neurophysiological mechanisms of this new process/the nature of the shared resources, and the conditions necessary to induce the formation of this new process.

While this dissertation provided evidence in favor of the integrated view, it does little to map out the exact behavioral and neurophysiological components of the integrated process. Additionally, while the results of these studies show that certain resources typically associated with WM and VA are shared in the new process this is likely not an exhaustive list. We have speculated that an expanded version of the dorsal attention network may be an ideal candidate for the underlying mechanism of these resources, but the nature of the studies in this dissertation do not allow for a definitive conclusion. It is important that future studies examine the nature/underlying mechanism of the resources shared by the new process in order to provide a better understanding of their composition. This exploration could begin with the use of fMRI technology to identify the anatomical regions associated with this new process. This information would help narrow the scope of additional studies necessary to specifically delineate the shared resources.

Additionally, while this dissertation did show the formation of the new process under the conditions of the paradigms explored, the results do not allow for any definitive conclusions to be made with regards to the exact conditions that allow for the formation of the identified new process. Future studies that delve into this aspect will allow for the better understanding of the new process formed when WM and VA are simultaneously deployed.

Final Conclusions

Three studies were conducted in an effort to probe the nature of the relationship between WM and VA. These studies compared the integrated view of this relationship with the parallel view, both described above. All three studies provided support for the integrated view. If replicated, the findings of this dissertation will have large effects on previously established work, including models of WM and VA and the shape of the attentional distribution, as well as future studies and task design.

The evidence that WM and VA form a new process has implications for the field of cognitive psychology. Specifically, it will argue for amendments to models of WM and VA. While current models contain a role for VA in the process of WM, none make claims about the nature of this relationship. These models may need to be revised to include the formation of a new process when WM and VA are used simultaneously. Additionally, future studies with paradigms that include both processes will need to be conscious that this integrated process will likely influence their results.

Experiment 2 also provided supplemental information to be applied to the existing knowledge of the shape of the attentional distribution. Here, it was found that under conditions of high WM load, there exists a region of processing enhancement surrounded by a region of suppression. However, when WM load was high, VA appeared to be widely distributed. Current views of the attentional distribution may need to account for its apparent association with the manipulation of WM load.

The findings from this dissertation strongly support the theory that WM and VA form a new, integrated process when simultaneously deployed. This finding has implications for the field of cognitive science—from study design and interpretation to the construction of models of WM and VA.

REFERENCES

Astle, D. E., Scerif, G., Kuo, B. C., & Nobre, A. C. (2009). Spatial selection of features within perceived and remembered objects. *Frontiers in Human Neuroscience*, *3(April),* 6.

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.

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

Baddeley, A. D. (2007). Working memory, thought and action. Oxford, England: Oxford University Press.

Baddeley, A. D., Allen, R. J., & Hitch, G. J. (2011). Binding in visual working memory: The role of the episodic buffer, *Neuropsychologia, 49(6),* 1393–1400.

Bahcall, D. O., & Kowler, E. (1999). Attentional interference at small spatial separations. *Vision Research*, *39(1),* 71–86.

Beauchamp, M. S., Petit, L., Ellmore, T. M., Ingeholm, J., & Haxby, J. V. (2001). A parametric fMRI study of overt and covert shifts of visuospatial attention. *Neuroimage*, *14(2),* 310-321.

Bleckley, M. K., Durso, F. T., Crutchfield, J. M., Engle, R. W., & Khanna, M. M. (2003). Individual differences in working memory capacity predict visual attention allocation. *Psychonomic Bulletin & Review*, *10(4),* 884-889.

Bonnel, A. M., & Hafter, E. R. (1998). Divided attention between simultaneous auditory and visual signals. *Perception and Psychophysics*, *60(2),* 179-190.

Bonnel, A. M., & Prinzmetal, W. (1998). Dividing attention between the color and the shape of objects. *Perception and Psychophysics*, *60(1)*, 113-124.

Braver, T. S., Paxton, J. L., & Locke, H. S. (2009). Flexible neural mechanisms of cognitive control within human prefrontal cortex. *Proceedings of the National Academy of Sciences*, *106(18),* 7351-7356.

Bressler, S. L, Tang, W., Sylvester, C. M., Shulman, G. L, Corbetta, M. (2008). Top-down control of human visual cortex by frontal and parietal cortex in anticipatory visual spatial attention. *Journal of Neuroscience, 28(40),* 10056-10061.

Brisson, B., & Jolicœur, P. (2007). The N2pc component and stimulus duration. *NeuroReport*, *18(11),* 1163-1166.

Broadbent, D. E. (1958). Perception and communication.

Broadbent D. E., & Broadbent M. H. P. (1987). From detection to identification: Response to multiple targets in rapid serial visual presentation. *Perception and Psychophysics, 42,* 105–113.

Carr, T. H., & Dagenbach, D. (1990). Semantic priming and repetition priming from masked words: Evidence for a center-surround attentional mechanism in perceptual recognition. *Journal of Experimental Psychology: Human Perception and Performance, 16(2),* 341–350.

Chen, Q., Marshall, J. C., Weidner, R., & Fink, G. R. (2009). Zooming in and zooming out of the attentional focus: an FMRI study. *Cerebral Cortex*, *19(4)*, 805-819.

Chen, Z., & Chan, C. C. (2007). Distractor interference stays constant despite variation in working memory load. *Psychonomic Bulletin & Review*, *14(2),* 306-312.

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

Clarke, E., McGarry, W. R., Bicksel, J., Thompson, J., Peterson, M., Strohl, J., Greenwood, P.M., Parasuraman, R., (November 2011). Cognitive training in healthy old age: Comparison of three training tasks on everyday cognitive functioning and white matter integrity. Poster presentation for SFN research conference.

Conway, A. R. A., Cowan, N., & Bunting, M. F. (2001). The cocktail party phenomenon revisited: The importance of working memory capacity. *Psychonomic Bulletin & Review*, *8*, 331-335.

Corbetta, M., Patel, G., and Shulman, G. L. (2008) The reorienting system of the human brain: from environment to theory of mind. *Neuron*, *58(3)*, 306-324.

Cowan, N. (1999). 3 An Embedded-Processes Model of Working Memory. *Models of working memory: Mechanisms of active maintenance and executive control*, 62. Cambridge University Press.

Cutzu, F., & Tsotsos, J. K. (2003). The selective tuning model of attention: psychophysical evidence for a suppressive annulus around an attended item. *Vision Research*, *43(2),* 205-219.

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

Dell'Acqua, R., & Sessa, P. (2006). Spatial attention freezes during the attention blink. *Psychophysiology, 43(4),* 394-400.

Della Sala, S., Gray, C., Baddeley, A., Allamano, N., & Wilson, L. (1999). Pattern span: a tool for unwelding visuo–spatial memory. *Neuropsychologia*, *37(10),* 1189-1199.

Deutsch, J. A., & Deutsch, D. (1963). Attention: Some theoretical considerations. *Psyhcological Review*, *70(1),* 80-90.

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

Downing P., & Dodds C. (2004). Competition in visual working memory for control of search. *Visual Cognition, 11(6),* 689–703.

Duncan J., Ward R., & Shapiro, K. (1994). Direct measurement of attentional dwell time in human vision. *Nature, 369*, 313–315.

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

Eriksen, C. W., Pan, K., & Botella, J. (1993). Attentional distribution in visual space. *Psychological Research*, *56(1),* 5–13.

Eriksen, C. W., & St. James, J. D. (1986). Visual attention within and around the field of focal attention: A zoom lens model. *Perception & Psychophysics*, *40*(4), 225-240.

Eriksen, C. W., & Yeh, Y. Y. (1985). Allocation of attention in the visual field. *Journal of Experimental Psychology: Human Perception and Performance, 11(5),* 583–597.

Foxe, J. J., & Simpson, G. V. (2002). Flow of activation from V1 to frontal cortex in humans. *Experimental Brain Research*, *142*, 139-150.

Fougnie, D., & Marois, R. (2009). Attentive tracking disrupts feature binding in visual working memory. *Visual Cognition*, *17*(1-2), 48-66.

Goldman-Rakic, P. S. (1996). The prefrontal landscape: implications of functional architecture for understanding human mentation and the central executive. *Philosophical*

Transactions of the Royal Society of London. Series B, Biological Sciences, *351(1346),* 1445-53.

Greenwood, P. M., & Parasuraman, R. (1999). Scale of attentional focus in visual search. *Perception and Psychophysics*, *61(5),* 837-859.

Greenwood, P. M., & Parasuraman, R. (2004). The scaling of spatial attention in visual search and its modification in healthy aging. *Perception and Psychophysics, 66(1),* 3-22.

Greenwood, P. M., Fossella, J. A., & Parasuraman, R. (2005). Specificity of the effect of a nicotinic receptor polymorphism on individual differences in visuospatial attention. *Journal of Cognitive Neuroscience*, *17(10),* 1611–1620. MIT Press.

Greenwood, P. M., Lambert, C., Sunderland, T., & Parasuraman, R. (2005). Effects of apolipoprotein E genotype on spatial attention, working memory, and their interaction in healthy, middle-aged adults: results From the National Institute of Mental Health's BIOCARD study. *Neuropsychology*, *19(2),* 199-211.

Greenwood, P. M., Lin, M. K., Sundararajan, R., Fryxell, K. J., & Parasuraman, R. (2009). Synergistic effects of genetic variation in nicotinic and muscarinic receptors on visual attention but not working memory. *Proceedings of the National Academy of Sciences*, *106(9),* 3633-3638.

Griffin, I. C., & Nobre, A. C. (2003). Orienting attention to locations in internal representations. *Journal of Cognitive Neuroscience*, *15(8),* 1176-94.

Hopf, J. M., Luck, S. J., Girelli, M., Hagner, T., Mangun, G. R., Scheich, H., & Heinze, H. J. (2000). Neural sources of focused attention in visual search. *Cerebral Cortex*, *10(12),* 1233-1241.

Hopf, J. M., Boehler, C. N., Luck, S. J., Tsotsos, J. K., Heinze, H. J., & Schoenfeld, M. A. (2006). Direct neurophysiological evidence for spatial suppression surrounding the focus of attention in vision. *Proceedings of the National Academy of Sciences of the United States of America*, *103(4),* 1053-1058.

Jolicœur, P., Brisson, B., & Robitaille, N. (2008). Dissociation of the N2pc and sustained posterior contralateral negativity in a choice response task. *Brain Research*, *1215*, 160-172.

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(2),* 169-183.

Kane, M. J., Conway, A. R., Hambrick, D. Z., & Engle, R. W. (2007). Variation in working memory capacity as variation in executive attention and control. *Variation in Working Memory*, 21-48.

Kim, Y. H., Gitelman, D. R., Nobre, A. C., Parrish, T. B., LaBar, K. S., & Mesulam, M. M. (1999). The large-scale neural network for spatial attention displays multifunctional overlap but differential asymmetry. *Neuroimage, 9(3)*, 269–277.

Klaver, P., Talsma, D., Wijers, A. A., Heinze, H. J., & Mulder, G. (1999). An event-related brain potential correlate of visual short-term memory. *NeuroReport*, *10(10),* 2001-2005.

Kramer, A. F. (1990). *Physiological Metrics of Mental Workload : A Review of Recent Progress*. *Internal Document* (pp. 1-51).

LaBar, K. S., & Gitelman, D. R. (1999). Neuroanatomic overlap of working memory and spatial attention networks: a functional MRI comparison within subjects. *Neuroimage*, *10,* 695-704.

LaBerge, D. (1983). Spatial extent of attention to letters and words. *Journal of Experimental Psychology: Human Perception and Performance, 9*, 371–379.

Lavie, N. (1995). Perceptual load as a necessary condition for selective attention. *Journal of Experimental Psychology: Human Perception and Performance*, *21(3),* 451-468.

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

Logie, R. H. (2011). The Functional Organization and Capacity Limits of Working Memory. *Current Directions in Psychological Science*, *20(4),* 240-245.

Logie, R. H., Cocchini, G., Della Sala, S., & Baddeley, A. D. (2004). Is there a specific executive capacity for dual task co-ordination? Evidence from Alzheimer's disease. *Neuropsychology, 18*, 504–513.

Luck, S. J., & Hillyard, S. A. (1994). Spatial filtering during visual search: Evidence from human electrophysiology. *Journal of Experimental Psychology*, *20(5),* 1000-1014.

Luck, S.J., & Vogel, E. K. (1997). The capacity of visual working memory for features and conjunctions. *Nature*, *390(6657*), 279-81.

Luo, Y. J., Greenwood, P. M., & Parasuraman, R. (2001). Dynamics of the spatial scale of visual attention revealed by brain event-related potentials. *Cognitive Brain Research*, *12*, 371-381.

Martinez, A., Anllo-Vento, L., Sereno, M. I., Frank, L. R., Buxton, R. B., Dubowitz, D. J., Wong, E. C., *et al.* (1999). Involvement of striate and extrastriate visual cortical areas in spatial attention. *Nature Neuroscience*, *2(4),* 364-369.

McCollough, A. W., Machizawa, M. G., & Vogel, E. K. (2007). Electrophysiological measures of maintaining representations in visual working memory. *Cerebral Cortex*, *43*, 77-94.

McNab, F., & Klingberg, T. (2007). Prefrontal cortex and basal ganglia control access to working memory. *Nature Neuroscience, 11(1),* 103-107.

Müller, H. J., & Humphreys, G. W. (1991). Luminance-increment detection: Capacity-limited or not? *Journal of Experimental Psychology: Human Perception and Performance, 17(1),* 107-124.

Müller, N. G., Mollenhauer, M., Rösler, A., & Kleinschmidt, A. (2005). The attentional field has a Mexican hat distribution. *Vision Research*, *45(9),* 1129-1137.

Noesselt, T., Hillyard, S. A., Woldorff, M. G., Schoenfeld, A., Hagner, T., Lutz, J., Tempelmann, C., *et al.* (2002). Delayed striate cortical activation during spatial attention. *Neuron*, *35*, 575-587.

Oh, S. H., & Kim, M. S. (2003). The guidance effect of working memory load on visual search. *Journal of Vision 3(9)*, 629a.

Oh, S. H., & Kim, M. S. (2004). The role of spatial working memory in visual search efficiency. *Psychonomic Bulletin & Review*, *11*(2), 275-281.

Olivers, C. N., & Eimer, M. (2011). On the difference between working memory and attentional set. *Neuropsychologia*, *49*(6), 1553-1558.

Ozaki, T. J. (2011). Frontal-to-parietal top-down causal streams along the dorsal attention network exclusively mediate voluntary orienting of attention. *PloS One*, *6(5),* e20079.

Parasuraman, R. (Ed.). (2000). *The attentive brain.* Mit Press.

Parasuraman, R., Greenwood, P. M., Kumar, R., & Fossella, J. (2005). Beyond heritability: Neurotransmitter genes differentially modulate visuospatial attention and working memory. *Psychological Science*, *16(3),* 200-207.

Perron, R., Lefebvre, C., Robitaille, N., Brisson, B., Gosselin, G., Arguin, M., & Jolicœur, P. (2009). Attentional and anatomical considerations for the representation of simple stimuli in visual short-term memory: Evidence from human electrophysiology. *Psychological Research*, *73*, 222-232.

Posner, M. I., Snyder, C. R., & Davidson, B. J. (1980). Attention and the detection of signals. *Journal of Experimental Psychology*, *109(2),* 160-174.

Postle, B. R. (2006). Working memory as an emergent property of the mind and brain. *Neuroscience*, *139(1),* 23-38.

Prinzel, L., Freeman, F., Scerbo, M., Mikulka, P., & Pope, A. (2003). Effects of a psychophysiological system for adaptive automation on performance, workload, and the event-related potential P300 component. *Human Factors*, *45(4),* 601-614.

Ranganath, C. (2006). Working memory for visual objects: complementary roles of inferior temporal, medial temporal, and prefrontal cortex. *Neuroscience*, *139(1),* 277-289.

Raymond J. E., Shapiro K. L., Arnell, K. M. (1992). Temporary suppression of visual processing in an RSVP task: An attentional blink. *Journal of Experimental Psychology: Human Perception and Performance, 18*, 849–860.

Reeves A., & Sperling, G. (1986). Attention gating in short-term visual memory. *Psychological Review, 93*, 180–206.

Robitaille, N., & Jolicœur, P. (2006). Effect of cue-target interval on the N2pc. *NeuroReport*, *17(15),* 1655-1658.

Robitaille, N., Jolicœur, P., Dell'Acqua, R., & Sessa, P. (2007). Short-term consolidation of visual patterns interferes with visuo-spatial attention: Converging evidence from human electrophysiology. *Brain research*, *1185*, 158-169.

Robitaille, N., Marois, R., Todd, J. J., Grimault, S., Cheyne, D., & Jolicœur, P. (2010). Distinguishing between lateralized and nonlateralized brain activity associated with visual short-term memory: fMRI, MEG, and EEG evidence from the same observers. *NeuroImage*, *53*, 1334-1345.

Ruchkin, D. S., Berndt, R. S., Johnson, R., Ritter, W., Grafman, J., & Canoune, H. L. (1997). Modality-specific processing streams in verbal working memory: evidence from spatio-temporal patterns of brain activity. *Brain research. Cognitive Brain Research*, *6(2),* 95-113.

Serences, J. T., Yantis, S., Culberson, A., & Awh, E. (2004). Preparatory activity in visual cortex indexes distractor suppression during covert spatial orienting. *Journal of Neurophysiology, 92(6),* 3538-3545.

Shapiro, K. L., Caldwell, J., & Sorensen, R. E. (1997). Personal names and the attentional blink: A visual "cocktail party" effect. *Journal of Experimental Psychology: Human Perception and Performance, 24*, 504–514.

Supèr, H., Spekreijse, H., & Lamme, V. A. (2001). A neural correlate of working memory in the monkey primary visual cortex. *Science*, *293(5527),* 120-4.

Todd, J. J., & Marois, R. (2004). Capacity limit of visual short-term memory in human posterior parietal cortex. *Nature*, *428(6984)*, 751-754.

Treisman, A. (1964). "Monitoring and storage of irrelevant messages in selective attention". *Journal of Verbal Learning and Verbal Behavior, 3(6),* 449–201.

Treisman, A. M., & Gelade, G. (1980). A feature-integration theory of attention.*Cognitive psychology*, *12*(1), 97-136.

Turner, M. L., & Engle, R. W. (1989). Is working memory capacity task dependent? *Journal of Memory and Language*, *28(2),* 127-154.

Vandenbroucke, A. R., Sligte, I. G., & Lamme, V. A. (2011). Manipulations of attention dissociate fragile visual short-term memory from visual working memory. *Neuropsychologia*, *49*(6), 1559-1568.

Vogel, E. K., Luck, S. J., & Shapiro, K. L. (1998). Electrophysiological evidence for a postperceptual locus of suppression during the attentional blink. *Journal of Experimental Psychology: Human Perception and Performance, 24*, 1656–1674.

Vogel, E. K., & Machizawa, M. G. (2004). Neural activity predicts individual differences in visual working memory capacity. *Nature*, *428*, 748-751.

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

Yago, E., Duarte, A., Wong, T., Barceló, F., & Knight, R. T. (2004). Temporal kinetics of prefrontal modulation of the extrastriate cortex during visual attention. *Cognitive, Affective & Behavioral Neuroscience*, *4(4),* 609-617.

Wickens, C., Kramer, A, Vanasse, L., & Donchin, E. (1983). Performance of concurrent tasks: A psychophysiological analysis of the reciprocity of information-processing resources. *Science*, *221(4615),* 1080-1082.

Woodman, G. F. (2003). The involvement of visual working memory in visual search. Dissertation Abstracts International: Section B: the Sciences and Engineering 63(7-B):3492.

Woodman, G. F., & Luck, S. J. (2002). Interactions between perception and working memory during visual search. *Journal of Vision, 2(7),* 732a.

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