Domain Disparity: Informing the Debate between Domain-General and Domain-Specific Information Processing in Working Memory.

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Dissertation Abstract

Domain Disparity: Informing the Debate between Domain-General and Domain-Specific Information Processing in Working Memory.

Working memory is a collection of cognitive resources that allow for the temporary maintenance and manipulation of information. This information can then be used to accomplish task goals in a variety of different contexts. To do this, the working memory system is able to process many different kinds of information using resources dedicated to the processing of those specific types of information. This processing is modulated by a control component which is responsible for guiding actions in the face of interference. Recently, the way in which working memory handles the processing of this information has been the subject of debate. Specifically, current models of working memory differ in their conceptualization of its functional architecture and the interaction between domain-specific storage structures and domain-general control processes. Here, domain-specific processing is when certain components of a model are dedicated to processing certain kinds of information, be it spatial or verbal. Domain-general processing is a when a component of a model can process multiple kinds of information. One approach conceptualizes working memory as consisting of various discrete components that are dedicated to processing specific kinds of information. These multiple component models attempt to explain how domain-specific storage structures are coordinated by a domain-general control mechanism. They also predict that capacity variations in those domain-specific storage structures can directly affect the performance of the domain-general control mechanism. Another approach focuses primarily on the contributions of a domain-general control mechanism to behavior. These controlled attention approaches collapse working memory and attention and propose that a domain-general control

mechanism is the primary source of individual differences. This means that variations in domain-specific storage structures are not predicted to affect the functioning of the domain-general control mechanism. This dissertation will make the argument that conceptualizing working memory as either domain-specific or domain-general creates a false dichotomy. To do this, different ways of measuring working memory capacity will first be discussed. That discussion will serve as a basis for understanding the differences, and similarities between both models. A more detailed exposition of both the multiple component model and controlled attention account will follow. Behavioral and physiological evidence will accompany the descriptions of both models. The emphasis of the evidence presented here will be on load effects: observed changes in task performance when information is maintained in working memory. Load effects can be specific to the type of information being maintained (domain-specific), or occur regardless of information type (domain-general). This dissertation will demonstrate how the two models fail to address evidence for both domain-specific and domain-general load effects. Given these inadequacies, a new set of experiments will be proposed that will seek to demonstrate both domain-specific and domain-general effects within the same paradigm. Being able to demonstrate both these effects will go some way towards accounting for the differing evidence presented in the literature. A brief conceptualization of a possible account to explain these effects will then be discussed. Finally, future directions for research will be described.

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Chapter 1: Introduction

Consider the everyday task of cooking a meal. First, one needs to maintain a goal that will guide a sequence of potentially disparate actions that may require vastly different types of information. For example, the first step in making a roast chicken is to prewarm the oven, then season the bird, arrange it in the pan, place it in the oven, and set the timer. These steps rely on a wide variety of different forms of information including, the spatial representations of the locations of task relevant objects in the kitchen, the identity of those objects from long term memory, a verbal list of ingredients, the recipe steps etc. In the face of this diversity of information, one also needs to integrate these domain-specific modalities to successfully monitor behavior and assess whether the tasks are completed in the appropriate order. For example, putting the chicken in a cupboard to cook would be a failure to integrate the verbal step of putting the chicken in oven with the spatial location of the oven. If this failure occurs, one needs a control mechanism that can modify behavior across domain-specific modalities according to task demands. Even this relatively simple task requires temporary maintenance and manipulation of multiple modalities of domain-specific information in concert with a domain-general mechanism which controls and monitors behavior across these modalities. The precise architecture of this broad system, henceforth working memory, remains a matter of debate. To what extent does the processing of domain-specific information integrate with a domain-general control mechanism?

Creating a better understanding about how different information modalities interact to influence behavior is important because understanding working memory is fundamental to understanding higher order cognition. For example, individual differences in working memory have been associated with, but not limited to, differences in reasoning ability (e.g. Kyllonen & Christal, 1990), reading comprehension (e.g. McVay & Kane, 2015), mathematical ability (e.g. Raghubar, Barnes, & Hecht, 2010), and educational and career success (e.g. Gottfredson, 1997). Further, disorders like attention deficit hyperactive disorder (e.g. Kofler, Rapport, Bolden, Sarver, & Raiker, 2010) and schizophrenia (e.g. Goldman-Rakic, 1994) show marked impairments in working memory. Thus, it is evident that working memory is integral to a diverse range of behaviors, as individuals with better working memory show better performance in these behaviors.

This dissertation will first give a brief overview of means of measuring working memory capacity. This will help to elucidate the extant debate in the literature in accounting for domain-specific and domain-general processes. A discussion of two distinct accounts of working memory will follow, along with the behavioral and physiological evidence that supports each. These discussions will focus on working memory load paradigms that manipulate task demands which can help elucidate the key differences between the predictions of the two accounts. For example, domain-general load effects occur when maintaining any kind of information depletes the resources required for performing a task, thus reducing performance (Lavie, 2000; Lavie, Hirst, de Fockert, & Viding, 2004). These effects occur regardless of the type of load, be it spatial or verbal etc. However, domain-specific load theories postulate that the kind of load can modulate performance, in some cases actually improving performance (Park, Kim, and Chun, 2007; Kim, Kim, and Chun, 2005).

This dissertation will demonstrate that the current literature shows evidence of both domain-specific and domain-general processes in working memory. One account of working memory known as the multiple component model, predicts that domain-specific effects will occur and affect performance. Another conceptualization of working memory is known as the controlled attention account. This account does not predict any domain-specific effects, rather that all performance is modulated by a domain-general control system, leading to domain-general effects. In the face of this disparity, a series of experiments will be detailed. These experiments will demonstrate both domain-general and domain-specific effects in the same paradigm. Doing so will go some way in accounting for the literature and set up a discussion of how to account for both effects in a more physiologically plausible manner. However, before discussing behavioral evidence for domain-specific and domain-general processes in working memory, it is useful to briefly review different methods for measuring working memory.

Chapter 2: Measuring Working Memory

Working Memory Capacity and Individual Differences

Simple span tasks require the participant to report a series of presented items such as digits or words, providing a measure of the storage capacity of short term memory. However, performance on these tasks failed to predict performance in areas such as reading comprehension and mathematical ability (Kane & Engle, 2002). In response to this, Daneman and Carpenter (1980) combined the storage aspect of the simple span task with an interleaved processing component, creating the first complex span task, known as the reading span. Here participants had to read a series of unrelated sentences and remember the last word of each sentence. They then had to recall the list of remembered words on a blank card. The numbers of sentences were then increased until the maximum amount of final words the participant could accurately recall was identified. Similarly, the operation span task (Turner and Engle, 1989) requires remembering a series of digits while performing a mathematical operation, and the symmetry span task (Kane et al, 2004) which requires symmetry judgments while maintaining a series of spatial locations. The operation, reading, and symmetry spans have been shown to reliably predict both reading comprehension (Daneman & Merikle, 1996; McVay & Kane, 2012) and mathematical ability (Unsworth & Engel, 2007). According to Redick et al (2012), performance in each of the three span tasks is also highly correlated. Previous studies have observed strong correlations between operation span and symmetry (r = .52) and reading span (r = .68). Reading span was correlated with symmetry span at r = .53 (Redick et al., 2012).

Given that the various span scores make use of different informational domains (verbal vs visual-spatial) it has been suggested that these scores measure, to a certain extent, domain-specific rather than domain-general resources. An example being the domain-specific storage systems in multiple component models of working memory (Baddeley and Logie, 1999). Thus, the predictive power of complex span scores in measuring working memory capacity might be tied to the similarity of the domain measured by the score required by the task. For example, Shah and Miyake (1996) found a verbal-spatial distinction between the symmetry and reading span in the prediction of spatial abilities. More recently, Thalmann and Oberauer (2015) investigated domain-specific interference within complex span measures. They manipulated the memory load type (visual-spatial vs verbal) and the interleaving letter processing task. Participants had to either make a rhyme judgement (verbal task) or a symmetry judgment (spatial task). They found that visual-spatial recall was impaired more by an interleaving visual-spatial task than an interleaving verbal task. Verbal performance was impaired more by an interleaving verbal task, than an interleaving visual-spatial task. This indicates that within the complex span paradigm, there is evidence that domain-specific effects can occur and affect performance

However, it has been proposed that the reading, operation, and symmetry span account for similar variance in both verbal and spatial ability tests (Kane et al, 2004). More recently, Vergauwe, Barrouliet, and Comos (2010) investigated this disparity using four complex span tasks that required *maintenance* of verbal or visual-spatial information, while *processing* either verbal or spatial information. They found that the tasks were equally predictive of working memory capacity regardless of whether the processing component was verbal or spatial. Thus it is clear that there has been a disparity in the literature in terms of what exactly complex span tasks are measuring Specifically, the contribution of domain-specific versus domain-general processes to performance. It is hoped that this dissertation will go some way to elucidate this distinction.

The distinction between whether these span scores measure a domain-general control system or contributions by domain-specific stores in an important one. If it is the case that span scores are equally predictive of performance across a wide range on informational domains, then it could be assumed they primarily measure a domain-general control system. However, if they differ in their prediction of performance as a function of the informational domain of the task, then they are also measuring contributions of domain-specific processes to performance. While the psychometric approach has been a useful means of assessing claims about working memory, understanding the physiology of the system is also important. In order to understand how working memory functions, one needs to have evidence for how the system is implemented in the brain. This evidence is useful in that it allows us to test the predictions made in the behavioral literature. For example, if it is claimed that there are domain-specific storage structures in a behavioral model, then it is reasonable to assume that one can observe those structures in the brain. If there is a distinction made between domain-specific and domain-general storage processes, that should be evident in the neural substrate. Simply, physiological observations allow us to both constrain and test the predictions and claims made by the behavioral models. This is turn allows us to come to a more accurate conceptualization of the working memory system.

Quantifying the Neural Substrate of Working Memory

There are a variety of ways of identifying the neural substrate that supports working memory. First considered are the fields of anatomy and physiology that have typically used monkey brains as an analogue for human brains. These studies have helped to elucidate the neural regions associated with the different processing components of the human working memory system. Early studies of the physiology of working memory looked at the implementation of the system in monkey brain. For example, single cell recording has been useful in determining the activation of different regions of cortex associated with various components of working memory tasks. Wilson, Ó Scalaidhe &

Goldman-Rakic (1993) had monkeys respond to either a stimulus that required a spatial response, or perform an object identification task. The activation of neurons in the prefrontal cortex were then measured. They found a dissociation between spatial and object domains in monkey prefrontal cortex. This is important as it indicates that the prefrontal cortex itself is to a certain extent organized in a domain-specific manner. Another useful tool has been the ability to measure the anatomical connectivity between different regions of cortex. For example, Cavada and Goldman-Rakic, (1989) found that prefrontal and posterior regions of monkey cortex share a wealth of reciprocal connections. This has been supported by the finding that a spatial working memory task increases metabolic activation of both prefrontal and posterior parietal regions in monkey cortex (Friedman and Goldman-Rakic, 1994). The findings observed with these methods are also useful in guiding hypotheses about how working memory is implemented in the human brain. As these methods are not practical to perform on human subjects, recent imaging technologies have allowed the investigation of whether the monkey studies can inform in implementation of working memory in human physiology.

These more recent studies have used fMRI to investigate working memory in human brains. These studies are useful in that they can show activation as a function of the processing of specific kinds of information, such as regions dedicated to spatial and verbal processing. It is also possible to determine how the activation patterns of regions dedicated to domain-general processing relate to those dedicated to more specific kinds of processing. For instance, it is possible to determine which areas of the brain are active when processing certain kinds of information such as objects and faces (Park, Kim & Chun, 2007). It is also possible to determine the neural regions responsible for the control processes in working memory (Osaka et al., 2003; Osaka et al., 2004). For example, an early fMRI paper found that prefrontal regions are activated when two tasks are performed at once but not alone. This indicates that the prefrontal regions are more active when increased cognitive control is required (D'Esposito et al, 1995). Further, by using techniques such a multi-voxel pattern analysis, one can predict (decode) the specific type of information being processed in a specific region of the brain based on neural activation patterns alone. One is also able to narrow down regions of the brain more dedicated to control processes (Lee, Kravitz, & Baker, 2013). In aggregate, these studies provide important biological constraints on models of working memory by revealing the organization and functional properties of working memory processes across the human brain. In the next sections, we will step through these two dominant models of working memory and the key evidence supporting each.

Chapter 3: Multiple Component Models of Working Memory

The working memory model was first proposed by Baddeley and Hitch (1974). In contrast to previous models of short-term memory, which emphasized only the storage of information, this model included both storage and processing of components. Working memory was considered to be an immediate memory system that could temporally maintain and manipulate information in accordance with task goals. Later refinements of the models (Baddeley, 1986/1996/2000) included two modality specific, capacity limited stores that processed visual and spatial information (visual-spatial sketch pad) and verbal information (phonological loop), see Figure 3.1. It also included a domain-general central executive component, which was responsible for the regulation of the contents of those stores while maintaining task goals. Later models included ‘rehearsal buffers’ for both storage components. An ‘episodic buffer’ was also included that maintained multi-modal episodic information retrieved from long term memory (Baddeley, 2000).

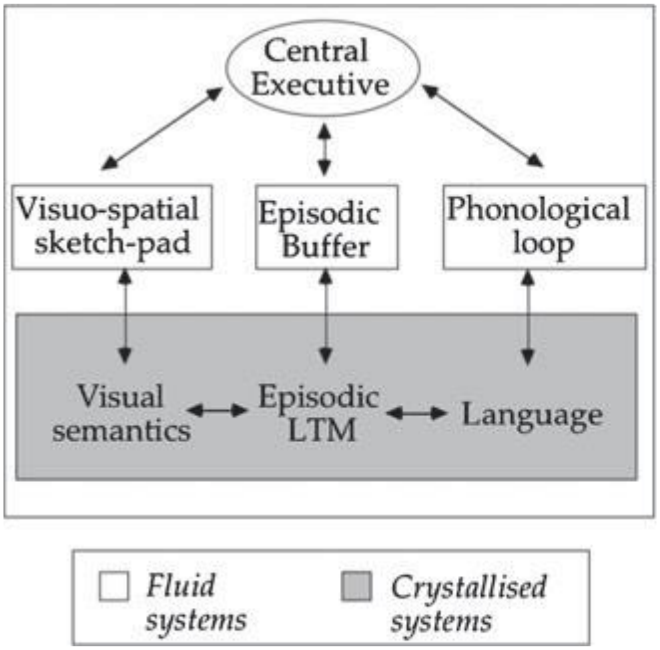

Figure 3.1: Baddeley’s Multiple Component Model of working memory (Baddeley, 2012).

This multiple component model with domain-specific resources is supported by neuropsychological findings which showed that damage to the left parietal cortex impairs verbal memory but leaves intact an ability to recall visual patterns. Conversely, damage to the right parietal cortex resulted in intact verbal but impaired visual memory (Logie, 2003). Thus, these multicomponent models view working memory as having multiple separable domain-specific functions with their own capacity limits. In these models, individual differences in performance arise from two sources. One source is variation in the function of domain-specific components. The other is variation in the function of the domain-general control mechanism.

While these models can be useful in conceptualizing the functional organization of working memory, they often fail to account for the multiple processes that underlie each component. For example, the visuospatial sketchpad as represented by the model is not neurally plausible in that components like the visuospatial sketchpad are sub-served by different neural regions. For instance, visual information about objects and space are processed separately in the brain, a finding supported by behavioral evidence *(*Klauer, & Zhao, 2004). Within the domain of object representation, the recall of information about specific types of objects has been shown to result in the activation of different brain areas (Martin, Wiggs, Cheri, Ungerleider & Waxby, 1996). Thus, the physiology suggests that there are many separable fluid systems which support many different types of representations. Accounting for these results would require a prohibitively vast and complex system by which the control system interacts with a variety of distinct storage systems. Thus, multiple component models are inadequate accounts of working memory in terms of accounting for the physiology of the working memory. To achieve a more complete understanding of working memory, one needs to consider the actual physiology of the brain. This will be detailed later in chapter 3. Having said that, the following sections discuss the behavioral and physiological evidence supporting multiple component models in detail.

Behavioral Predictions and Evidence

As has been previously discussed, working memory is inherently capacity limited. When that capacity is used up, the ability of the individual to perform a task diminishes. In the case of the Stroop task, reducing the available capacity for processing will usually result in increased interference as compared to when working memory is not burdened. The increase in interference as is what is known as a load effect. These load phenomena can help us investigate the specificity of information processing in working memory. According to load theory, working memory maintains processing priorities by specifying relevance of stimuli, while high working memory load increases distractor interference by impeding inhibitory cognitive control over the interference from the irrelevant distractor (Lavie et al., 2004; Lavie, & de Fockert, 2005).

However, evidence for domain-specific processing in working memory has motivated research into load *specific* effects, in that the type of load being maintained could modulate distractor interference. Multiple component models suggest that information domains such as verbal and spatial information are processed using separate cognitive resources, and do not necessarily rely on a common attentional resource (Coccini, Logie, Della Sala, MacPherson, Baddeley, 2002; Foungie, Zughni, Godwin, and Marois, 2015; Yi et al., 2004). Thus, it is possible that the effects of load will manifest as being domain-specific. Accordingly, following discusses various working memory load paradigms that give evidence for multiple component models of working memory.

Visual search paradigms are one way in which researchers have attempted to investigate the effect of load on working memory. Typically, these experiments involve the participant searching for a target in an array while maintaining a working memory load. Woodman, Vogel and Luck (2001) sought to investigate the role visual working memory plays in visual search. Participants had to maintain up to 4 items (objects) in working memory while performing a visual search. They found that a visual working memory load did not modulate the efficiency of visual search. A later study by Woodman and Luck (2004) sought to determine whether the maintenance of a spatial load would affect visual search efficiency. They proposed that the lack of interference in the earlier paper could be because spatial and non-spatial information are stored in separate working memory subsystems. Consistent with this theory, the authors used the same paradigm but added a spatial load, which resulted less efficient search. Memory accuracy also decreased as a function of set size. These findings provide evidence for separable spatial and object working memory systems.

Another domain-specific effect in the visual search literature is known as memory driven attentional capture. Here, the content of information being held in working memory can bias attention *towards* objects with the same content. In that regard, Olivers, Meijer, and Theeuwes (2006) sought to provide evidence for memory driven attentional capture. In the first experiement, participants were presented with a memory item where they had to remember the color of a disk. They then had to perform a visual search consiting of a number of disks and a diamond shaped-target. The distractor disk in this instance was of a unique color from the rest of the array. The participants were then presented with 3 color disks and asked to indicate the memory disk. It was predicted that when the memory load matched that of the distractor, response times would increase as attention will be driven to that content of working memory, in this case the distractor. Results showed that while there was an overall load effect, there were no-load specifc effects in that the interference effect was not particular to the color held in memory. The authors postulated that this could be due to the fact that participants in the first experiment were using verbal memory to encode the color rather than visual memory. In the second experiment, the authors attempted to encourage participants to use more visual memory as opposed to verbal memory. They did this by using subtle variations of the same color of the memory test. Again it was predicted that they would find increased interference when the memory load matched the distractor, specifically when particiapants were encouraged to use visual memory, rather than verbal memory. Results showed that in the visual condition there was increased interference when the memory load matched the distractor, a finding indicating memory driven capture. These findings were supported in subsequent experiements where participants showed an increase in interference when participants encoded distracor related features. The occurrence of these load specific effects indicates that the mainentance of content can result in increased attentional capture when that content matches the distractor.

In a related study, Soto, Humphreys and Heinke (2006; Exp 1) assessed the effects of working memory load on visual search efficiency. They found that even when the target was not presented in the working memory load, visual search was affected in that participants were biased towards the memory shape resulting in an increase in interference. Similarly Soto and Humphreys (2006) conducted a study using patients with damage to the parietal lobe and had subsequent visual extinction of contralesional stimuli. They found that then the contralesional stimulus matched that of a previously presented memory load, there was a reduction in visual extinction. This provides strong evidence that a working memory load can in fact drive memory-driven attentional capture. However, memory driven attentional capture is not the only example of domain-specific effects.

Specialized load theory (Park et al., 2007; see also Kim et al., 2005) suggests that information is processed in working memory according to resource specific stores and that each of those resources have their own independent capacity limitations, see Figure 3.2. This means that maintaining a concurrent working memory load that consumes resources required for target processing, will impair target selection as the resources for processing that kind of information are diminished. However, if the concurrent working memory load consumes resources that are required for distractor processing, then interference will be reduced as the resources for processing the distractor are diminished.

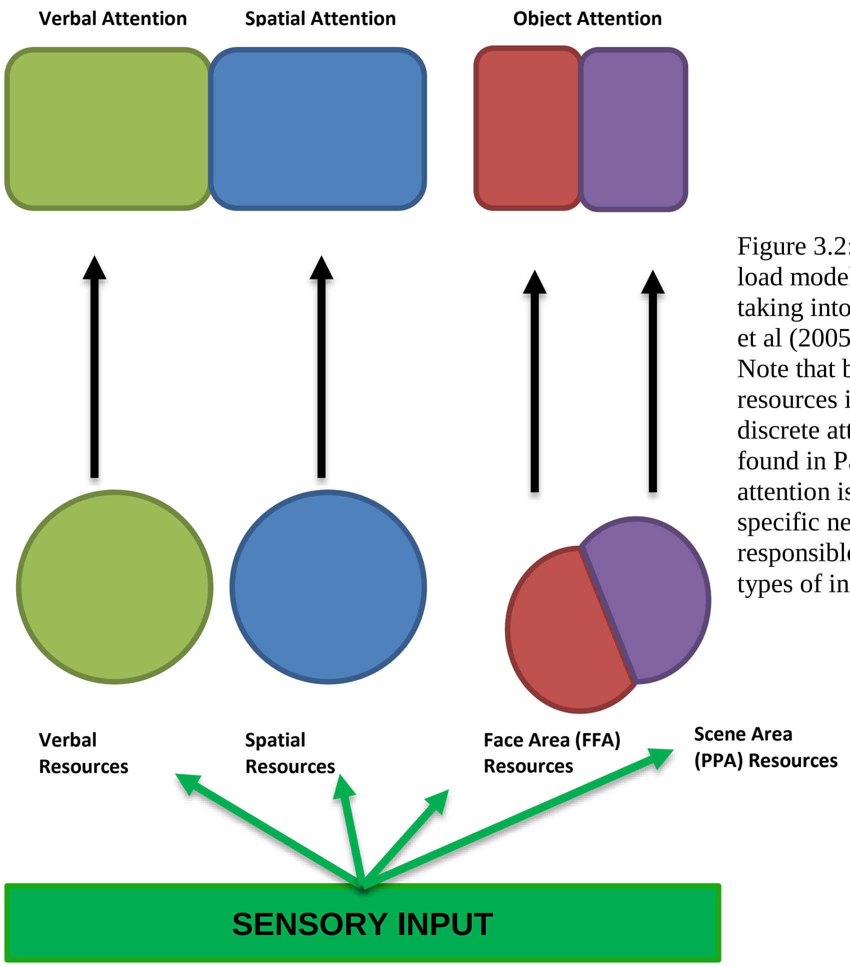

Figure 3.2: A simplified specialized load model of working memory taking into account findings of Kim et al (2005) and Park et al (2007). Note that both the domain-specific resources interface with their own discrete attentional components. As found in Park et al (2007), object attention is broken down into specific neural components responsible for processing different types of information.

Kim et al (2005) sought to investigate the possibility that different types of working memory load may have different effects on attentional selection depending on whether the load overlaps with the target or distractor. They hypothesized that the maintenance of a verbal load would affect the processing of a verbal distractor thus increasing interference, the same as would be predicted by domain-general load theory.

However, contrary to the prediction of domain-general load theory that performance will be impaired regardless of type of load, they predicted improved performance and reduced interference when the load matched the distractor because the working memory load would tie up limited capacity mechanisms required for distractor processing. Using a Stroop paradigm, they tested these predictions. In Experiment 1A they used a verbal load and a meaning comparison task where participants had to determine if a color patch matched the target color word. They predicted increased Stroop interference because the load matched target. In Experiment 1B they used a spatial load which would not overlap with the verbal target. Results showed that increased target related load interference relative to the spatial condition in 1B. In Experiment 2 they used a verbal load that overlapped with distractor processing using a color comparison Stroop task. Participants had to decide whether the ink on a color swatch was the same as the distractor word. The word could be *SAME* or *DIFF*, providing verbal based distraction. Experiment 2A used a verbal load which should decrease Stroop interference, as it overlapped with the distractor. Experiment 2B used a spatial working memory task which should have no effect on interference. As predicted, results showed a decrease in interference in Experiment 2A relative to Experiment 2B meaning that there was no interference effect in the load condition. Experiment 3 used a manipulation that allowed the loading of load on either the target or the distractor. Results showed verbal load increased interference when it matched the target by decreasing resources available for target processing. On the other hand, a spatial load decreased resources available for distractor processing thus decreasing interference, see Figure 3.3. When there is overlap with target processing, performance is impaired, and when there is overlap with distractor processing, performance is facilitated. Thus, according to the authors the results support the idea that there are dissociable attentional capacity limitations in the encoding and processing of verbal, color and spatial information.

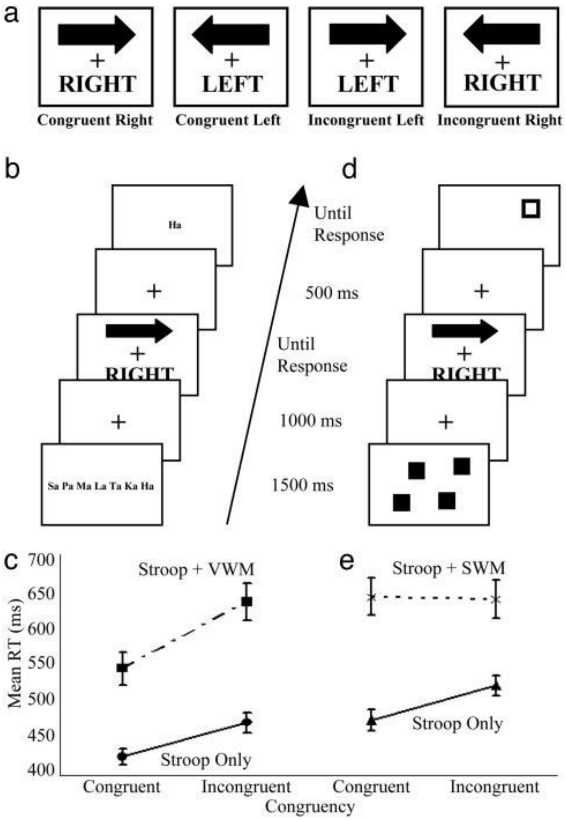

Figure 3.3: Experiment 3 - Target-relevant working memory load increased Stroop interference, whereas distractor-relevant working memory load decreased it. (a) The left right decision Stroop task display conditions used in experiments 3A and 3B. (b) Schematic trial of experiment 3A, which required maintenance of verbal information while performing the left right-decision Stroop task. (c) Mean RTs for each condition in experiment 3A. Stroop interference increased in the dual-task condition. (d) Schematic trial of experiment 3B, which required maintenance of spatial information while performing the left right-decision Stroop task. (e) Mean RTs for each condition in experiment 3B. Stroop interference decreased in the dual-task condition.

I have elaborated upon two theories that attempt to explain load specific effects. The specialized load theory suggests that the maintenance of a memory load will result in a depletion of resources for processing that kind of information, resulting in a decreased capacity to process that information. Thus, if the memory load matches the target, performance will decrease as there are reduced resources for processing that information. If the working memory load matches the distractor, performance would be facilitated. This is contrary to the predictions of memory-driven capture which suggests that attention is biased towards the information being held in working memory. If the working memory load matched the target, performance would improve while if the working memory load matched the distractor, interference would increase. A recent study sought to explain these different observations.

Minamoto, Shipstead, Osaka and Engle (2015) sought to investigate the conflicting results between specialized load theory and memory driven attentional capture. As previous studies investigating memory driven capture only used a low working memory load, they hypothesized that the size of the load is responsible for whether specialized load theory or memory driven attentional capture are predictive of the results. This manipulation is motivated by findings that interference decreases under high distractor related working memory load (Kim et al. 2005; Park et al. 2007; Soto and Humphreys, 2008). However, it’s possible that low load may bias attention towards load related information (Soto et al. 2006; Olivers et al, 2008). They sought solve this contradiction by demonstrating that low amounts of distractor load can impair attention as predicted by memory-driven attentional capture, while high distractor load would reduce interference as is predicted by specialized load theory. Their results failed to replicate specialized load findings of Park et al (2007) where the load matched the distractor and reduced response times relative to the no-load condition. Further, the response time pattern in the high load condition matched the predictions from domain-general load theories where the load type did not modulate processing of the distractor. Simply, distractor interference increased as a function of increased load. They concluded that these results suggest that a low load directs attention towards stimuli of that load type as predicted by memory-driven attentional capture. However, the authors failed to demonstrate specialized load effects for either low load or high load conditions. The fact that the load effects were not modulated by working memory capacity indicates that memory-driven attentional capture is a bottom-up process not subject to cognitive control processes. This also indicates that domain-specific storage structures can directly influence control processes. This something which the controlled attention view cannot account for, as it views capacity limitations as being primarily the result of a domain-general attentional control mechanism. Further support for multiple component models can be also found in the physiological evidence.

Physiological Predictions and Evidence

The below discusses the physiological evidence for multiple component models of working memory. As said previously, multiple component models consist of a domain-general central executive, and domain-specific information stores. Thus, one would expect that information from different domains would be processed in neural regions responsible for processing that kind of information. Further, one would expect to see separable activation of the neural regions responsible for control processes.

Useful research that can provide context for the notion of separable neural regions associated with working memory, is work that has looked at the neural basis of visual representations. This is important as this research shows that different neural regions and pathways are specialized to process different kinds of information. Early physiological research suggested a segregation between the two main visual processing streams in the brain, namely the ventral and dorsal streams. The ventral stream is associated with the visual identification of objects, while the dorsal stream is associated with spatial vision (Goodale and Milner, 1992) and spatial working memory (Friedman and Goldman-Rakic, 1994). In humans, neuropsychological evidence has shown that lesions to the dorsal and ventral areas produces dissociable deficits. Specifically, a patient known as DF with a bilateral lesion to the occipitotemporal area and a smaller lesion of the occipitoparietal cortex showed an inability to identify objects but intact spatial ability to reach objects and shape her grasping hand to reflect object size. She could also not orient her hand to be the same as a distant slot but could to so when reaching (James, Culham, Humphrey, Milner and Goodale, 2003). This indicates, that like the monkey brain, the dorsal and ventral streams are dedicated to two different types of information processing. A more recent paper by Kravitz et al (2011) characterizes the dorsal ‘how’ stream into three distinct neural pathways. A parieto–prefrontal pathway, a parieto–premotor pathway and a parieto–medial temporal pathway. The pathway of most interest here is the parieto-prefrontal pathway which supports spatial working memory.

In that regard, Cavada and Goldman-Rakic (1989) investigated the connections between the posterior parietal cortex and frontal lobe in Rhesus monkeys. They found that all fronto-parietal connections in are reciprocal, indicating anatomical connectivity within the fronto-parietal network. These connections were found to establish connections between multiple limbic and sensory regions within the parietal cortex with the frontal regions. This is important as it shows physiological evidence for the neural implementation of spatial working memory in monkey cortex. Further evidence for the role of this network in spatial working memory was demonstrated by, Friedman and Goldman-Rakic (1994). They used the 14C-2-deoxyglucose (2DG) method which measures local cerebral glucose utilization in monkey cortex. They showed that in a working memory task, the dorsal lateral prefrontal cortex and parietal cortex was associated the mnemonic components of the task and spatial related sensory motor demands respectively. Further, these physiological studies have shown that these regions do not exist in isolation but rather as a fronto-parietal network of which one job is to support working memory processes. However, they do indicate different processing responsibilities of each neural region. The below reviews fMRI evidence that shows activation patterns which support the physiological findings of how working memory is implemented in the brain. Specifically, activation in different regions of the brain as a function of the type of information being maintained.

In an early imaging paper showing evidence for domain-specificity of processing. Smith, Jonides and Koeppe (1996) sought to dissociate the neural mechanisms underlying verbal and spatial working memory using PET. Participants had to maintain verbal or spatial information and activation patterns for verbal and spatial working memory were then compared. Results showed that in the spatial condition, all four significant activation areas were found in the right hemisphere. These included the ventrolateral prefrontal cortex, occipital cortex and parietal cortex with the last two being consistent with visuospatial processing. These are also regions associated with the fronto-parietal network. In the verbal condition, activation was seen in Brodmann area 40 in parietal cortex, and three separable regions in frontal cortex, corresponding to Broca's area, premotor regions, and the supplementary motor area. This indicated that verbal load activated mostly left hemisphere regions while spatial load activated mostly right hemisphere regions. The next experiment consisted of a continuous memory task using a stream of stimuli (verbal or spatial). The same activation patterns were observed for the spatial and verbal tasks as seen in the first experiment. These findings show that the neural basis of verbal working memory is distinct from spatial working memory.

In another study investigating these load specific effects Park et al. (2007) proposed the specialized load theory which suggested that different types of working memory load may be independent of each other. They suggest that information is not processed in a single unitary system but rather different kinds of information are processed in specific neural regions of the brain, a claim supported by neuroimaging research. Simply, when the working memory load does not share the same neural resources as the target or distractor, they should *not* interfere with task performance. To do this, Park et al. used two separate object categories, faces and houses as neural imaging research has shown they are processed in separate regions of the brain. Specifically face perception involves activation in the fusiform face area (FFA; Kanwisher et al., 1997), and house perception involves activation in the parahippocampal place area (PPA; Aguirre, Detre, Alsop, & D’Esposito, 1996). Participants had to maintain a working memory load of either faces or houses which either loaded on the target (face) or distractor (house). They predicted that in conditions where the working memory load type and target overlapped, distractor interference would be similar to conditions with no-load. In conditions where the working memory load type and distractor overlapped, there would a decrease in distractor interference. Results showed that there was greater response conflict when the load type was the same as the target, similar to the no-load condition. When the load type overlapped with the distractor, there was a reduction in interference as compared to the no-load condition. These results indicate working memory capacity is contextually limited by the kinds of concurrent information being processed. In other words, processing only verbal stimuli will quickly reach the processing capacity of that neural region, while processing additional spatial stimuli may not tap the resources required by the verbal regions, allowing more spatial information to be processed.

In a more recent study Lee, Kravitz and Baker (2013) used fMRI to determine the contribution of brain regions to the processing of visual and non-visual information. In the visual task, participants had to identify whether an object fragment was part of the cued stimuli. In the non-visual task, participants had to indicate the whole probe was part of the same category as the cued object. Results showed that both the lateral prefrontal cortex (lPFC) and posterior fusiform cortex (pFs) were activated during the delay. The activation of the lPFC is associated with working memory tasks and the pFs is associated processing memory for visual objects. When participants were engaged in the visual task, there was stronger activation in the pFs, while when they were engaged in the nonvisual task activation in the lPFC was stronger. These results indicate that different kinds of information are processed in distinct regions of the brain and the activation of those regions is predicated by the control of working memory according to task demands.

Further, the data indicates that the lPFC can be involved with both maintenance and control. This indicates that while the processing of information can be domain-specific, that processing is modulated by a common top down control resource in accordance with task demands.

The previous has discussed physiological evidence for the multiple component models and the distinction between domain-specific storage structures. The following will discuss a different way of conceptualizing working memory. Specifically, the following models suggest that individual differences arise out of variation in function of the domain-general control mechanism, and place far less emphasis on the contribution of domain-specific components.

Chapter 4: Working Memory as Attention

Before the introduction of Baddeley's working memory model, simple span tasks were used to measure the capacity limitations of domain-specific short term memory resources. These span tasks require the participant report a series of presented items such as digits or words. As said previously performance on these tasks failed to predict performance in other areas of complex cognition. Thus, when researchers introduced a processing component to tap Baddeley's central executive (Baddeley, 1986), they were far better able to account for variation in performance between individuals (Kane & Engle, 2002). It is this domain-general control mechanism that is the primary source of individual variation in task performance in the following related models.

In the Embedded-Process Model of working memory (Cowan, 1988/1995/1999), see Figure 2, the information contained in working memory comes not from domain-specific storage structures like the visual-spatial sketch pad and phonological loop as in Baddeley’s model, but rather from currently activated long term memory (LTM) traces within the focus of attention. Attention here is the enhancement of the processing of some information to the exclusion of other information, a process controlled by a domain-general central executive (Cowan, 1999). According to this model, attention is controlled by both voluntary top-down processes via the central executive and involuntary bottom-up processes via the attentional orienting system. Further, the amount of information that can be focused on at one time is limited, as are the amount of LTM traces that can be actively maintained at one time. This capacity limit sits at around 4 items of information that can be actively maintained/focused upon in working memory (Cowan, 2010).

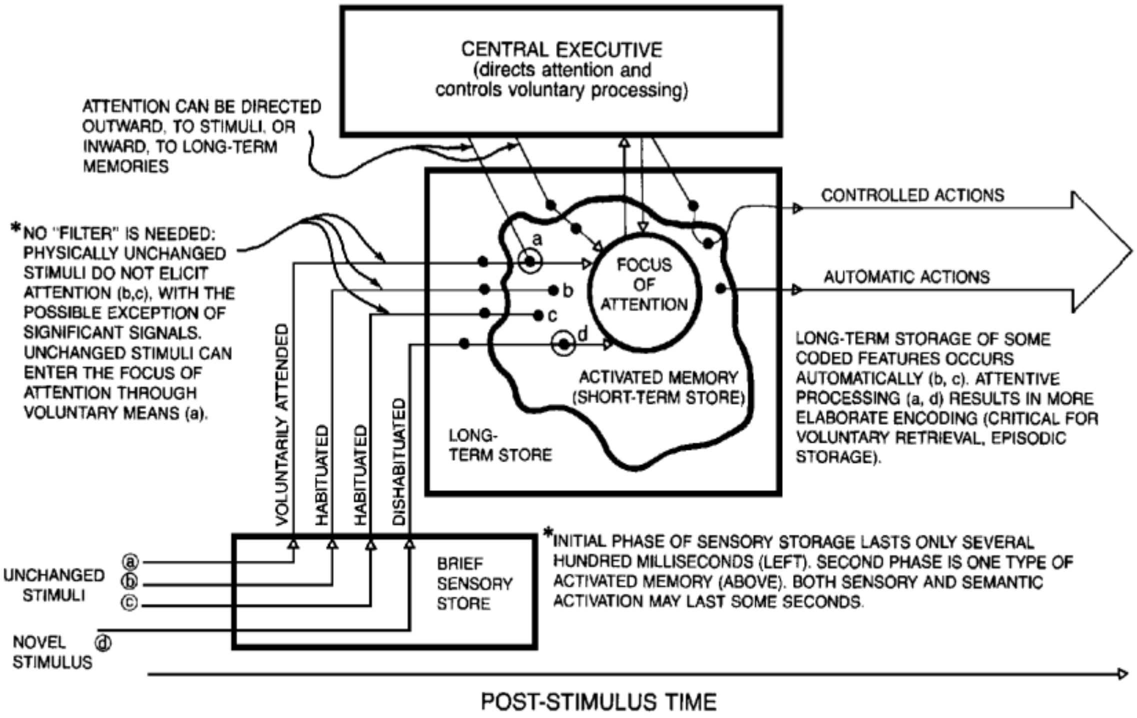

Figure 4.1: Cowan's Embedded Process Model of working memory. Time since stimulus presentation is represented ordinally along the x axis. The components are arranged in real time, and stimulus reception can be present in more than one component at the same time. Short-term storage is represented as an activated subset of long-term storage, and the focus of attention is represented as a subset of short-term storage. Habituated stimuli do not enter the focus of attention. The timing involvement of the central executive in processing is flexible. The arrows represent the transfer of information from one form to another; these are discrete approximation to continuous processes that can occur in parallel or cascade. Pathways leading to awareness can come from three sources: changed stimuli for which there is dishabituation, items selected through effortful processing (whether or sensory origin or not), and the spontaneous activation of long-term memory information based upon associations (not shown). Printed from "Evolving conceptions of memory storage, selective attention, and their mutual constraints within the human information processing system by Cowan, N, 1988, Psychological bulletin. Copyright 1988 by the American Psychological Association.

A related model of working memory was proposed by Kane, Bleckley, Conway, and Engle (2001). The controlled attention model proposes that working memory processes reflect both a controlled attention central executive and short term memory processes and that they are both highly related but distinguishable constructs. For example, Engle, Tuholski, Laughlin, and Conway (1999) used structural equation modeling to show that while the performance in working memory tasks showed a strong relationship with short term memory tasks and fluid intelligence tasks, the short-term memory tasks did not show a relationship with fluid intelligence, a correlate of higher order cognition. According to the authors, these findings indicate that it is not storage processes that are important to working memory's relationship to higher order cognition, but rather the functioning of the central executive. While the inclusion of the central executive in the model is compatible with other the multiple component models by Baddeley (1996), the controlled attention model predicts that individual differences in task performance arise not from capacity limitations in domain-specific storage components, but rather from primarily from the ability of the individual to exert domain-general attentional control. The controlled attention approach is useful in that it focuses on one aspect of the system. That focus makes for a simpler conceptualization of the source of individual differences in working memory. Namely the ability to focus attention while rejecting distracting information. However, a problem with this view is that one loses the ability to investigate the contribution of domain-specific processes that support the control processes of the working memory system. This would prevent achieving a full theoretical understanding of the mechanisms underlying working memory. That being said, the following details behavioral evidence for the important role of the domain-general control mechanism plays with regards to individual differences.

Behavioral Predictions and Evidence

Complex span tasks tax not only short term memory processes, but control processes as well. It has been found that doing so allowed them to predict performance in a variety of domains. Thus, researchers sought to understand how the control mechanism contributed to individual differences. In that regard, Kane et al (2001) proposed the controlled attention model of working memory that sought to show that working memory capacity is reflective of the ability of the individual to actively maintain information, and to control attention in the face of irrelevant information. Given that, one would expect that individuals with high working memory capacity would be able to better control attention. This would be reflected by better response times in tasks with distracting elements when compared to individuals with low working memory capacity. Accordingly, the following provides behavioral evidence that working memory capacity reflects the domain-general ability to control attention.

A popular means of testing attentional control is through the use of an antisaccade task. In these tasks, participants must inhibit an eye movement to the same location as a cue. In that regard, Kane et al (2001) used an anti-saccade task with a visual cue, which could either inform the location of the target letter (prosaccade) or indicate that the participant should inhibit a saccade towards that location (antisaccade). Working memory capacity was measured with the operation span task. They predicted that high and low working memory capacity individuals would not differ in the prosaccade task which involves automatic attentional orienting, rather they would exhibit differences when preventing orienting towards the antisaccade cues which requires active attentional control. Results showed that the prosaccade task allowed for faster target identification but no differences between high and low span individuals. There were significant response time differences between high and low span individuals in the antisaccade task. These results showed that high span individuals were better able to resist having attention captured by the cue and/or were faster at disengaging attention from the cue and focusing on the target. Further, these results suggest that individual differences are indicative of differences in the ability to control attention in the face of distraction.

A later study by Unsworth, Engle and Schrock (2004) used a similar antisaccade paradigm. When the prosaccade and antisaccade trials were blocked, they found that both high and low working memory capacity individuals were faster on prosaccade rather than antisaccade. Further high working memory capacity individuals were faster on the antisaccade trials than the low working memory capacity individuals. This indicated the high working memory capacity individuals were better in trials which required high levels of attentional control. They then mixed the prosaccade and antisaccade trials, a manipulation designed to increase the amount of required attentional control. This is because the mixing of trials increased the need for goal maintenance as the task goal was not continually reinforced (Unsworth et al, 2004). Results showed that both groups were faster in prosaccade than antisaccade trials. Low working memory capacity individuals were slower and less accurate on both prosaccade and antisaccade conditions than high working memory capacity. Importantly, in contrast to their previous finding, low working memory capacity individuals were slower in the prosaccade task than antisaccade task. This indicated that they were making antisaccades in prosaccade trials. These findings again indicate that individual differences are indicative of the ability to maintain task goals while actively maintaining information in the face of distraction.

In a later study Lavie and de Fockert (2005) demonstrated how an unrelated working memory load can affect distractor rejection in visual search by increasing the saliency of the distractor. In the first experiment, participants had to search for a circle in diamonds and respond to the direction of the line within it. On some trials an irrelevant color singleton distractor was present. They included a no-load (single task) and high working memory load condition where participants had to recall a set of letters (dual-task). They predicted that interference from the singleton would be higher under to working memory load condition. Results confirmed that attentional capture by task irrelevant distractors was far higher when working memory was loaded. The following experiment consisted of both a no-load and high load condition. The load condition was a successor digit naming task where participants had recall the order of memory probe digits. The results again showed that a working memory load increased distractor interference compared to the no-load condition. Thus, these results demonstrate that attentional capture by an irrelevant distractor in a visual search task can be modulated by working memory load of an unrelated (numerical) domain. This would indicate domain-general load effects as the domains of the distractor and target are not related but still evoke consistent interference.

Further evidence for domain-general load effects was found by Morey and Cowan (2004). They sought to determine if verbal working memory and visual working memory are subject to a shared limitation controlled by a domain-general central executive. They used a two digit, seven-digit and seven-digit single load digit condition (participant’s phone number). The load was spoken out loud while the participants performed a change detection task with four colored squares. If visual information is encoded partly through verbal encoding, then there should be interference between verbal and visual tasks. Further, if the performance on the visual array relies on cross-domain limits, then there should only be interference in the seven-digit load condition. Results showed decreased accuracy only in the seven-digit load condition and not in the two-digit load or seven-digit single load conditions. These findings support the idea that working memory is supported by a domain-general control resource and that conflict can occur across different domains. Further support for the primary role a domain-general control mechanism plays in working memory can be found in the physiological evidence.

Physiological Predictions and Evidence

As has been previously discussed, the controlled attention approach focuses on the roll that the domain-general central executive plays in task performance. Thus, much of the following physiological evidence pertains to the differences in activation patterns in the control regions of the brain, such as the prefrontal and anterior cingulate cortices. Specifically with regards to the relationship between working memory capacity and the ability to detect and respond to conflict. According to the controlled attention account, one would expect activation patterns in the prefrontal control regions that reflect increased response to and detection of conflict, as well the prevention of the encoding of irrelevant information. Further, one would expect these effects to be modulated by working memory capacity. Individuals with high working memory capacity would show activation patterns associated with better conflict resolution and distractor rejection than individuals with low working memory capacity. Accordingly, the following shows physiological evidence for the relationship between the central executive and the manifestation of individual differences.

Support for the role of working memory capacity plays in attentional control has been provided by numerous fMRI studies (Osaka et al., 2003; Osaka et al., 2004; Sohn et al., 2008). Osaka et al (2003) investigated the relationship between working memory capacity, and the implementation of the dorsal lateral prefrontal cortex (DLPFC) and anterior cingulate cortex (ACC) in responding to conflict. The authors used a listening span test (LST), an auditory version of the reading span, to determine high and low span individuals. They used the LST again in the fMRI to compare neural activation patterns of the listening span task (dual-task) to that of a single task condition which involved the basic recall of letters with no processing component. The authors predicted that in the dual task conditions, there would be greater activation of the DLPFC and ACC when compared to the single task condition. This would be due to increased demands on cognitive control processes. Further they predicted that there would be significant differences between the activation patterns of the ACC and DLPFC between the high and low span individuals in the dual task condition. As predicted the results showed increased DLPFC activation during the LST than during single task conditions for both high and low span individuals. Differences between the high and low span individuals were also evident in the activation patterns of the ACC. Only high span individuals showed increased activation as a result of increased working memory demands. These results suggest that a major contributing factor to performance is predicted by the ability to detect and respond to conflict and the corresponding activation of prefrontal control regions.

Similarly, Osaka et al (2004) hypothesized that activation under a reading span task (dual task) would increase in both the ACC and PFC and that there would be differences in activation patterns between the high span and low span individuals when compared to a read-only task (single task). Like Osaka et al (2003), they predicted no differences between the low and high individuals in the read-only condition, but there would be significant group differences in activation patterns in the reading span task. The results confirmed this prediction. In the high span condition, activation in the ACC was greater in the high-span group than in the low span group in the dual task condition. Further structural equation modeling indicated that the activation pattern of the ACC to the DLPFC was positive for the high span group and negative for the low span group, suggesting that more effective attentional control was associated with closer co-operation between the DLPFC and ACC. Thus, the authors concluded that there is a general domain-general neural basis for attentional control. Further, differences in activation patterns in regions associated with these cognitive control processes are related to individual differences in working memory capacity. These findings support the idea that efficient attentional control is modulated by the capacity of working memory. It's important to note that these findings show that domain-general control processes contribute a significant amount to the overall effectiveness of the working memory system. However, they do not speak to the contributions of the rest of the system to behavior not accounted for by control processes.

Electronic encephalogram (EEG) research has also provided physiological evidence for the relationship between a domain-general control mechanism and individual differences. For example, Miller, Watson, and Strayer (2012) used even related potentials (ERPs) to investigate the different activation patterns between high and low span individuals in the interference rich context of a Simon task. The authors predicted that working memory capacity would be related to the magnitude of the error related negativity (ERN) signal, a decrease in the signal observed following the detection of an error. There would also be an observed change in magnitude of the Pe (post-error positivity) signal, a positive increase in the signal following the detection of an error. Specifically, high working memory capacity individuals would show higher ERN signals following an error as a result of using enhanced PFC function to bias conflict processing in the ACC. High working memory capacity individuals would also show a higher Pe signal which is associated with an awareness of errors and updating of cognitive strategies according to task goals. Results showed that working memory capacity modulated the magnitude of the ERP signals. High working memory capacity individuals showed both increased ERN and Pe signals following an error compared to those individuals with low working memory capacity. Taken together, the combination of these ERN/Pe signatures suggests individuals with greater working memory capacity have a more finely tuned attentional control network and, therefore, were more likely to monitor potential sources of interference.

In a related study Vogel, McCullogh and Machizawa (2005) assessed individual differences in the ability to prevent encoding irrelevant distractors in working memory. This was done using ERP’s to distinguish the neural patterns between high and low capacity individuals. Specifically, the authors measured an ERP waveform of contralateral delay activity (CDA) that reflects maintenance and encoding of information. They used this measure as CDA asymptotes according to capacity limits (Vogel & Machizawa, 2004). It would be assumed that high capacity individuals are better able to control attention and prevent the encoding of irrelevant information. To test this, participants were presented with an array of red and blue rectangles of varying orientations. They were asked to remember the orientations of only the red items in either the left or the right hemi-field as represented by a cue. The participants then had to identify if any of the object in the array had changed on the subsequent trial. If participants failed at the task, they would encode both the blue and red items in the cued hemisphere. Working memory capacity was measured using a change detection paradigm. Results showed that high capacity individuals were more efficient at rejecting irrelevant information than low capacity individuals. Further, they indicate that low capacity individuals stored more information in memory than high capacity individuals. This indicates that a major source of individual differences in task performance arise out of the ability to control attention in the face of distraction, in accordance with task goals.

This dissertation has discussed support for both accounts of working memory. The following attempts to demonstrate that focusing on the hard distinction between domain-specific and domain-general processing in working memory is counter-productive to creating a comprehensive account of the system.

Chapter 5: Addressing the False Dichotomy

This dissertation has discussed several aspects concerning the relative specificity of information processing in working memory. The working memory system is a collection of cognitive resources that are involved with the maintenance and manipulation of information according to task goals. This system is inherently capacity limited in terms of the amount of information that can be maintained at once. However according to the working memory as attention view of working memory, individual differences arise not from the amount of information that an individual can maintain but rather the ability of a domain-general mechanism to complete task goals in the face of interference. According to load theory, when the working memory system is loaded, it taxes this domain-general attentional control system which results in what are known as load effects. However, research has shown that the kind of load can modulate the amount of interference in what are known as load specific effects. One theory that seeks to explain load specific effects is memory driven attentional capture. This suggests that the kind of information being maintained will bias attention *towards* the same kind of stimuli. While this suggests a bottom up influence on attentional control, and a way in which domain-specific resources can affect cognitive control. Contrary to the predictions of memory driven capture, the specialized load theory suggests that maintaining a concurrent working memory load that consumes resources required for target processing in a selective attention task will impair target selection. Alternatively, if the concurrent working memory load consumes resources that are required for distractor processing then interference will be reduced as the resources for processing the distractor are diminished. This theory indicates that these domain-specific resources have discrete attentional control capacities, a finding contrary to the controlled attention account of working memory. This debate between domain-general and domain-specific models speak towards how discrete specific resources, and control processes are, and in what way they interact to affect attentional control. Evidence for both processes has been extensively covered in this dissertation. In that regard, the following will seek to demonstrate that focusing on the distinction between domain-specific and domain-general control is counterproductive. The false dichotomy that this debate knowingly or not creates, leads to models and conceptualizations that fail to reflect the actual nature of the working memory system.

The Problems with the Multiple Component Model

The above has discussed evidence for both domain-specific and domain-general information processing in working memory. The point of a scientific model is to create a testable conceptualization of a system which furthers understanding of the processes which underlie its functioning. If the model is too simplistic, you lose the ability to understand the nuance and intricacies of the system as a whole. In that regard, the multiple component model fails to provide a physiologically sound model of working memory.

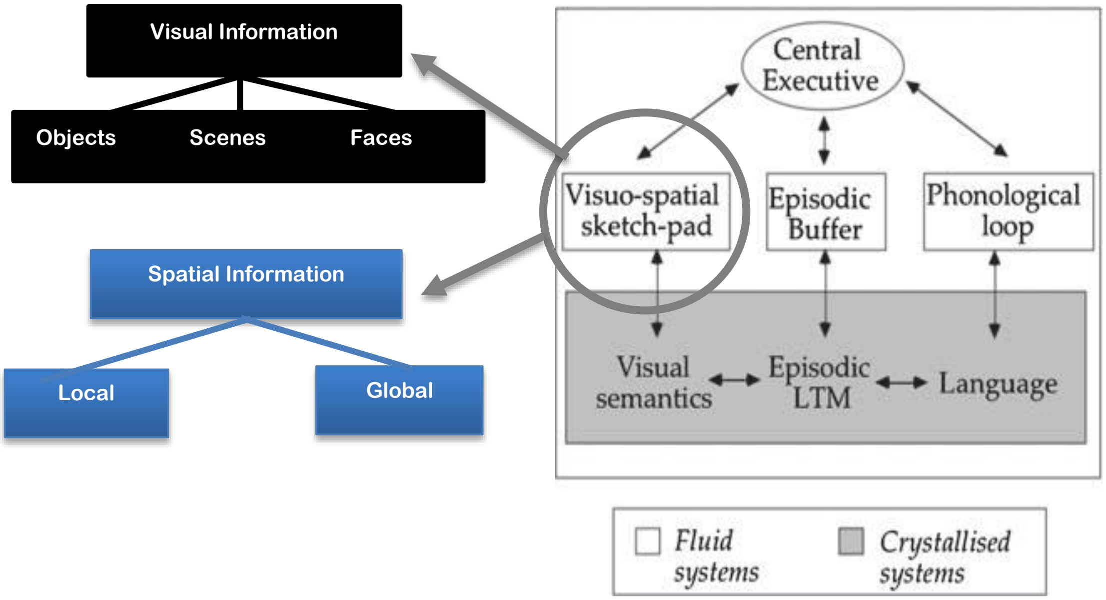

Figure 5.1: The blow out represents the possible additions to the visuospatial sketch pad in order for the model to be more physiologically plausible. Note how visual and spatial information can be broken down into for specific processes.

Consider the make-up of the model. It includes various domain-specific storage structures that interface with related components in long term memory. At first glance this seems like a reasonable and physiologically plausible model of the working memory system. However, a simplified box model would miss the intricacies of the system and prevent us from fully understanding it. That is the case with these storage structures. The blow out, see Figure 5.1, details an example of what it would take to more accurately represent the elements of information processing that the visual-spatial sketch pad would have to be comprised of. For example, visual and spatial information are processed separately in the brain, a finding supported by behavioral evidence *(*Klauer, & Zhao, 2004). Therefore, the model would need an added level of complexity to account for this. Further, those different processes are also comprised of various other components. For example, visual processing can include the processing of faces, scenes and objects, all of which are supported by different neural regions. Thus, to adequately model working memory, one would need to keep adding boxes, ad infinitum. This is an untenable proposition and is a weakness of the multiple component model. Specifically, when it comes to making testable predictions about the processes which sub-serve each box, they are ill specified at each stage.

The Problems with the Working Memory as Attention Model

According to the working memory as attention model, information contained in working memory consists of currently activated traces in long term memory. The information that is attentded to is determined by a domain-general control mechanism. This conceptualization is different the multiple component models in that it focuses less on the effect that domain-specific stores have on behavior. Rather, sensory information is fed into short term stores that interface with long term memory processes (see figure 4.1) which in turn are controlled by a domain-general control mechanism. However a problem that both models share is how the domain-general control mechanism interfaces with the rest of the memory system. When performing a task the control mechanism needs to recruit the appropriate congitive resouces in order successfully complete it, see Figure 5.2. By accepting the controlled attention model, one needs to account for the problem that the control mechanism needs to have direct access to the precise location of information from numerous domains. This would also mean that the frontal lobes would need a very precise set of connections with every cortical region in order to drive the activation of particular subpopulations of cells. Physiologically it is not the the case that the prefrontal regions have the vast number of connections required to make this possible. As said previously, a physiologically sound account of working memory is important to creating a more accurate account of the system. Given the weaknesses of both models, the follwoing details a possible approach that can take into account the physiology while still explaining the behavioral literature.

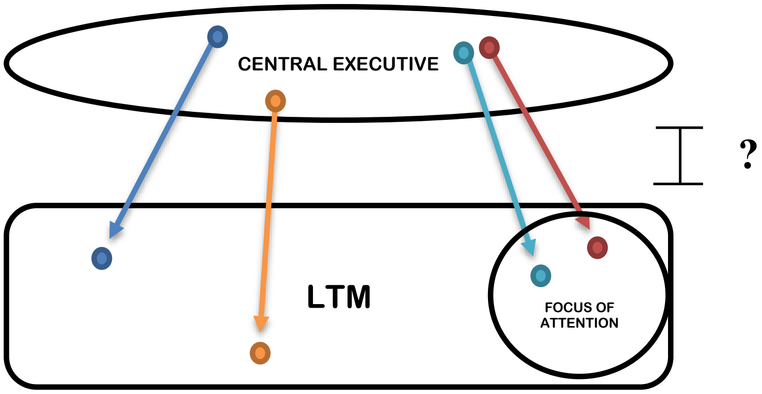

Figure 5.2: A demonstration of how the domain-general central executive would need to have direct access to specific pieces of information long term memory. The color circles indicate those indexes in the central executive. The question mark indicates that the working memory as attention account fails to demonstrate how, physiologically, the central executive interfaces directly with long term memory.

Addressing the Disparity

Both the multiple components models and working memory as attention models view the control mechanism as domain-general. However taking that view, the central exectutive must have connections with domain-specific components whether they are in discerte stores, or in long term memory. This would mean that to at least some extent the central executive *has* to be domain-specific and in that it processes information from different information domains. Therein lies the problem with both models. They fail to account for the the control mechansim interfaces with a multitude of domains. This is party due to the false dichotomy of the domain-specific versus domain-general debate.

The new approach cannot be either or, but rather sould consist of a graded hiearchy that allows very specific information at the single neuron level to reach high level semantic processing recruiting, a vast *network* of neural regions. If that is the case, then it should be possible to observe both domain-specific and domain-general effects in the same paradigm. Again consider the graded heirachy approach. The rejection of distracting information would be processed by the central executive which is at the top of the heirachy of processing. Thus any interference effects observed here would be shown to be *primarily* domain-general. However, domain-specific effects would be observed in instances where more domain-specific aspects of the working memory system are tapped. For example one would expect a measure of working memory that taps verbal processing would be more predicitve of recall of that specific kind of information. This would be because that measure is tapping a lower, more domain-specific part of the heirachy. Accordingly, the below details a series of experiements designed to test the feasibility of this new approch in predicting task performance in a working memory load paradigm.

Chapter 6: Current Experiments

The evidence presented in this dissertation speaks towards a more nuanced view of the intersection between domain-specific and domain-general processes. In that regard, the following details an experimental paradigm that allows for the testing of the claims made by both the working memory as attention, and the multiple component approaches. The first component involves predicting the pattern of load effects as a function of each model. To do this, one needs to manipulate the type of information of being maintained. That information can either match the target, or match the distractor. One then needs to be able to measure how a matching working memory load with either the target, or distractor, would affect load effects. According to the multiple component model, a working memory load that matches the target would reduce processing capacity for that kind of information. Thus, interference would increase, as the resources for processing the target are reduced. If the load matched the distractor, interference would decrease as the processing capacity for the distractors is reduced. However, according to the working memory as attention approach, a matching working memory load is irrelevant to the functioning of a domain-general control component thus interference would increase regardless of load type.

Table 1 shows four proposed experiments with varying load, target, and distractor types. It also indicates the predicted amount of interference by each model. For instance, in experiment one, the verbal load matches the target, but does not match the distractor. According to the multiple component model, this would use up resources for target processing, making it more difficult to respond to the target, increasing interference. The controlled attention approach does not predict that interference would be modulated by load type and accordingly, predict high interference. In experiment 2, the spatial load matches the spatial distractor. According to the multiple component model, the spatial load would use up resources for processing the spatial distractor, which would affect the processing of that distractor. This would result in a low amount of interference. As said previously, the controlled attention approach does not predict modulation of interference by load type and would thus predict high interference. An account which attempts to integrate the findings from the working memory load literature would predict that interference would be high for all conditions. This is because most of the variance would come from differences in domain-general control processes. While there could be variation as a function of load, target, and distractor types, this would be small and not easily measurable. In order to measure domain-specific contributions, one needs to measure the capacity for those resources and whether individual differences predict performance in each task. The predictions for experiments three and four will be detailed in the methods section.

Table 1

Each proposed experiment and their respective target and distractor types as well as the predicted amount of interference by each model.

Experiment	Load Type	Target Type	Distractor Type	Multiple Component	Controlled Attention
Experiment 1	Verbal Load	Verbal	Spatial	Higher	Present
Experiment 2	Spatial Load	Verbal	Spatial	Lower	Present
Experiment 3	Spatial Load	Spatial	Verbal	Higher	Present
Experiment 4	Verbal Load	Spatial	Verbal	Lower	Present

*Compared to interference as predicted by the controlled attention model.

Another component is the measurement of working memory capacity for both spatial (symmetry span) and verbal (operation span) domains and using those measures to predict performance in an interference paradigm e.g. a variation of a Stroop task. As each span makes use of different information domains, one can make predictions about how much variance each span would explain in each experiment as a function of each model (see Table 2). In experiment one, the verbal load matches the verbal target. According to the multiple component model, verbal and spatial resources have their own capacity limitations. Performance in this task would be best predicted by individuals with higher verbal working memory capacity as they are better able to process both the verbal load, and the verbal target. Thus, the operation span would be the best predictor of performance. The controlled attention approach views complex span tasks as being a measure of domain-general cognitive resources and that predictions of performance are would not be sensitive to different information domains. Therefore, it would predict that neither the operation nor the symmetry span would be significantly better predictors of performance in the task. In experiment two, the spatial load matches the spatial distractor. Here the multiple component model would explain more variance in performance on the task than the operation span. Unlike experiment one, individuals with higher symmetry spans would have excess processing capacity to process the distractor, resulting in an increase in interference. Those with lower spans would have those resources used up, reducing the ability to process the distractor, decreasing interference. Again, the controlled attention approach does not predict that either the operation span or symmetry span would be significantly better predictors of performance in the task.

The final component is the prediction of performance in the recall of the working memory load as a function of span task. In the following experiments the type of load can either be verbal or spatial. Similarly, we use a verbal complex span and a spatial complex span. According the multiple component model the verbal span should be significantly better at predicting performance at recalling verbal information than the spatial span. Likewise, the spatial span should be significantly better at predicting performance with regards to recall of spatial information. However, according the controlled attention approach, the span scores would not differ in their ability to predict performance in the recall of either verbal or spatial information. This is because the complex span tasks are a domain-general measure of working and are not designed to be sensitive to different predicting performance in different tasks. As mentioned earlier in the dissertation, operation and symmetry spans have been shown to reliably predict both reading comprehension (Daneman & Merikle, 1996; McVay & Kane, 2012) and mathematical ability (Unsworth & Engel, 2007). However, previous research has shown a verbal-spatial distinction between the symmetry and reading span in the prediction of spatial abilities (Shah and Miyake, 1996; Thalmann and Oberauer (2015). The demonstration of this verbal-spatial distinction would help elucidate the contribution of domain-specific processes to complex span tasks and working memory.

Table 2

Each proposed experiment and the span measure which will best predict task performance in the ***probe*** *task according to each model.*

Experiment	Load Type	Target Type	Distractor Type	Multiple Component	Controlled Attention
Experiment 1	Verbal Load	Verbal	Spatial	OPSAN	N/A*
Experiment 2	Spatial Load	Verbal	Spatial	SSPAN	N/A*
Experiment 3	Spatial Load	Spatial	Verbal	SSPAN	N/A*
Experiment 4	Verbal Load	Spatial	Verbal	OSPAN	N/A*

*The Controlled Attention model would not predict significant differences in the variance explained by each span task.

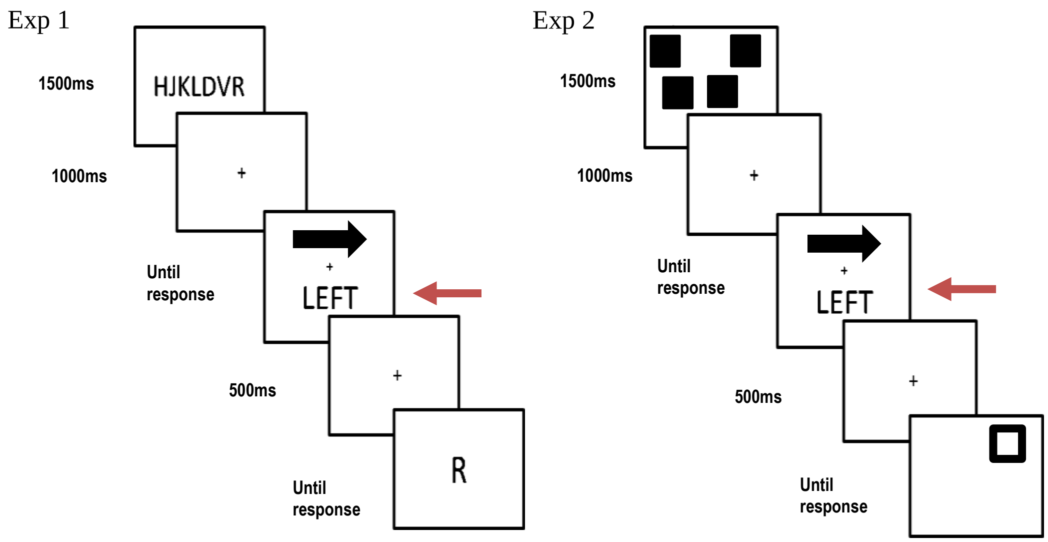

Figure 6.1: An example of a single incongruent 'yes' trial for Experiment 1 and Experiment 2. The red arrow indicates the target.

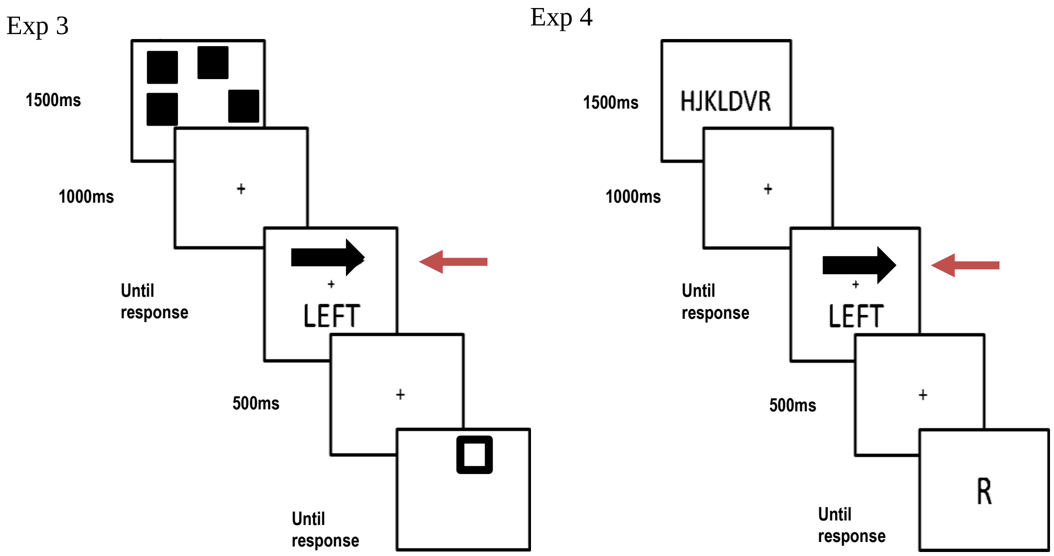

Figure 6.2: An example of a single incongruent 'yes' trial for Experiment 3 and Experiment 4. The red arrow indicates the target.

General Methods

Experiments 1-4 are based upon the modified Stroop task used by Kim et al (2005: Exp 3). All experiments test the effects that the maintenance of a working memory load will have on target and distractor processing. Each experiment differ in the type of load and type of target (see Table 1). All experiments involve both verbal *and* spatial information content. E-Prime 2.0.10 software (Psychology Software Tools, Pittsburgh, PA) was used to code and administer Experiments 1-3. Experiment 4 was coded using Psytoolkit, a web-based online experiment design environment (Stoet, 2010; 2017). Participants for Experiments 4 were recruited using Amazon Turk. Working memory capacity was administered using E-Prime 2.0.10 and measured in Experiments 1-3 using the Automated operation span and Automated symmetry span tasks (Unsworth, Heitz, Schrock, & Engle, 2005). Experiment 4 used equivalent online versions of the Operation span and Symmetry span run on a web based Inquisit platform (Inquisit 5, Millisecond software).

Chapter 7: Experiment 1

Methods

Experiment 1 used a verbal load and a verbal target. In the Stroop component, participants were required to identify the word 'LEFT' or 'RIGHT', while ignoring the orientation of a distractor arrow which could be pointing left or right. In the working memory load condition, participants had to maintain a seven-letter load while performing the Stroop task. Here, both the target and the working memory load required verbal processing.

According to the multiple component approach, we would expect to see an increase in interference as the verbal load reduces the capacity for the processing of the verbal target. Here the operation span would be significantly more predictive of performance than the symmetry span as it is testing the capacity of the verbal component of the working memory system. According to the controlled attention account, we would expect to see an increase in interference in the Stroop task in the load condition compared to the no-load condition regardless of load type. Both the operation span and symmetry span scores would be equally predictive of performance. In terms of probe accuracy, the multiple component model would predict that the operation span would be a better predictor of the recall of verbal working memory load than the symmetry span. The controlled attention approach would not predict that there would be a significant difference in terms of the amount of variance each span accounts for.

Participants. Participants were 139 undergraduate students at The George Washington University. All subjects had healthy and normal or corrected to normal vision. They received class credit for participation.

Stimulus, Procedure, and Design. The stimuli were black colored words and arrows with a central fixation (Figure 6.1). The target words were either ‘LEFT’ or ‘RIGHT’ in all caps, in Arial font. The distractor arrows were size matched to the words and could be pointing left or right. The identity of the word was randomized each trial, as was the orientation of the arrow. The distractor arrows could be presented randomly above or below the target words. There were two conditions, congruent and incongruent. In the congruent condition the orientation of the distractor arrow matched the direction implied by the target word. In the incongruent condition, the orientation of the distractor arrow did not match the direction implied by the target word.

Figure 6.1 details the procedure. In the single task condition, participants had to respond to the word ‘LEFT’ with the ‘s’ key and the word ‘RIGHT’ with the ‘l’ key. In the dual task condition, participants had to maintain a seven-letter load while performing the Stroop task. They had to then indicate whether a presented letter was part of the memory set or not. If it was they responded with the ‘p’ key. If it was not, they responded with the ‘q’ key. There was a practice block of 20 trials. A single-task block or dual-task block of 64 trials each followed. The order of these blocks were randomly selected after the practice block. The resulting experimental design of Experiment 1 was a (2) condition × (2) congruency design, with span as a between participants variable.

Results

Outlier exclusion. First, a trial by trial analysis was conducted for each participant. Any trial with an RT below 200ms or above 2000ms in the Stroop task was excluded. All participants who achieved a mean RT of more than 2.5 standard deviations for the Stroop task were excluded from all RT and accuracy analysis. For the RT analysis of the Stroop task, in the load condition, only the trials in which the participant was accurate in the probe, were included in analysis. All participants who achieved a mean accuracy of equal to or below 50% for the working memory probe, (performance equal to chance), were excluded from all RT and accuracy analyses. Only participants who completed all three tasks (Stroop, OSPAN, and SSPAN) were included. A total of 46 participants were excluded according to these criteria (n=93).

Accuracy. In the no-load condition Stroop task mean accuracy was 97% compared to a mean accuracy of 97% for the Stroop task in the load condition. A 2 (condition) x 2 (congruency) ANOVA was run. There was no main effect of load [F (1, 92) = .137; $P > 0.05$], but there was a main effect of congruency [F (1, 92) = 52.25; $P < 0.0001$] indicating that participants were less accurate in the incongruent conditions. There was no interaction between load and congruency [F (1, 92) = .110; $p > 0.05$] indicating that there was not a significant decrease in accuracy as a function of load.

When including OSPAN as a between subject factor, we observed a main effect of congruency [F (1, 91) = 56.131; $p < 0.0001$]. No other interactions were observed. When including SSPAN as a between subject factor, we observed a main effect of congruency [F (1, 91) = 52.095; $p < 0.0001$]. No other interactions were observed.

Probe Accuracy. Mean accuracy for the verbal working memory probe was 81%. Correlation analyses were conducted on the relationship between OSPAN, SSPAN, and probe accuracy. We tested the relationship between OPSAN and SSPAN and found a significant positive correlation [r =.411; p <0.0001; n=93]. When then modeled the span scores on probe accuracy independently. The OSPAN score significantly predicted accurate recall [r =.389; p <0.0001; n=93]. Removal of 2 outliers (n=91) strengthened the relationship [r=.45; p <0.0001; n=91] but the difference was not significant. The SSPAN also significantly predicted accurate recall [r=.305; p <0.001; n=93]. Removal of one outlier strengthened the relationship but again, this difference was not significant [r =.35; p <0.0001; n=92]. These correlations were not statistically different from each other. As the OSPAN, SSPAN and probe accuracy are all significantly correlated, two partial correlations were run in order to identify the individual contributions of each span to probe accuracy. First we ran a partial correlation to better identify the relationship between probe accuracy and the two span scores. When controlling for SSPAN in the model, OSPAN significantly and positively correlated with probe accuracy [*r* =.303; *p* <0.002; df=90]. However, when controlling for OSPAN in the model, SSPAN demonstrated a weaker positive correlation [*r* =.173; *p* <0.05; df=90], although the two were not statistically different.

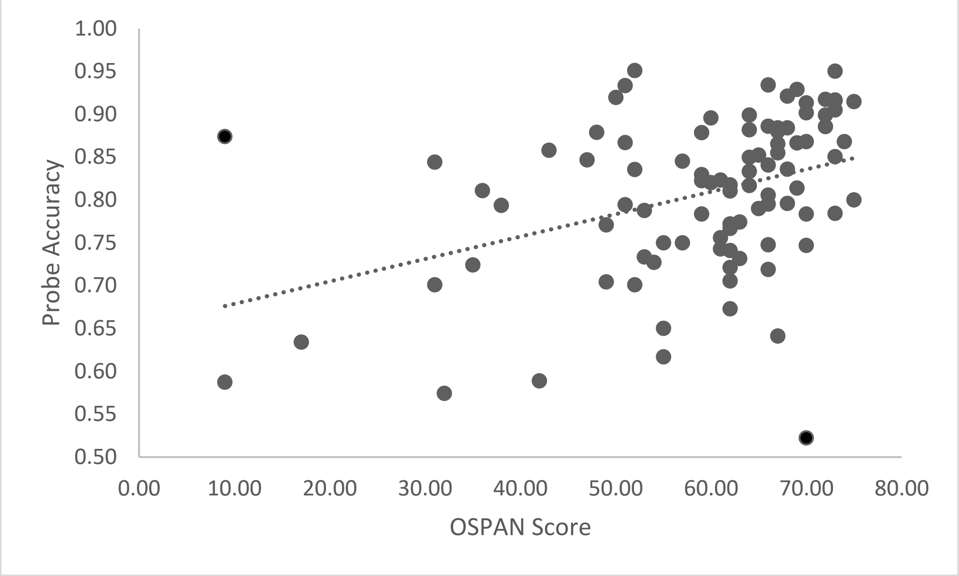

Figure 7.1: Scatterplot showing the relationship between probe accuracy and OSPAN scores. The darker points are outliers.

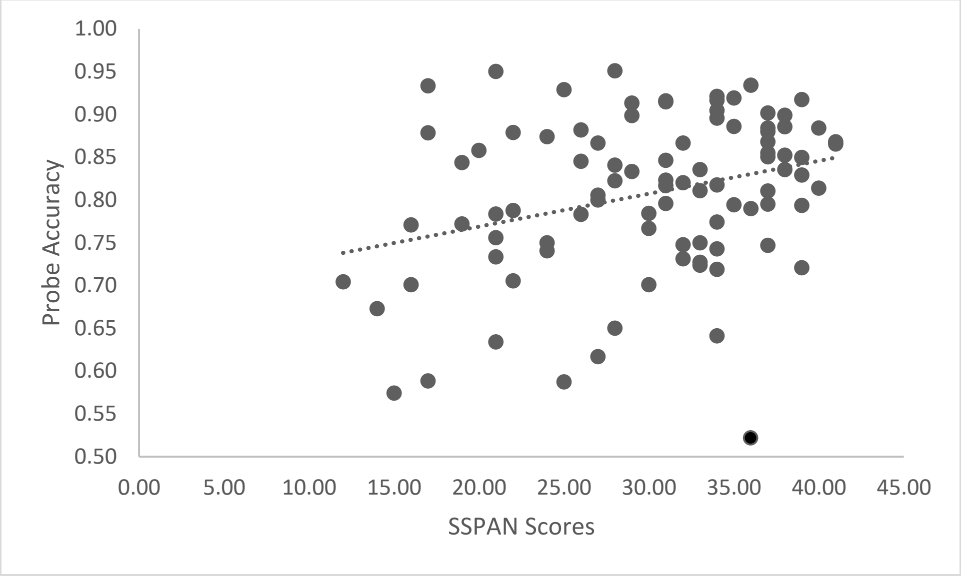

Figure 7.2: Scatterplot showing the relationship between probe accuracy and SSPAN scores. . The darker point is an outlier.

Response Times. We first ran a 2 (condition) x 2 (congruency) ANOVA to check for interference patterns. We found a main effect of load [*F* (1, 128) = 81.084; *p* < 0.0001], indicating that participants were overall slower in the load condition. We also found a main effect of congruency [*F* (1, 128) = 81.084; *p* < 0.0001]. There was no significant interaction between load and congruency.

We then performed a median split of the data based on OSPAN scores (n=46). A 2 (condition) x 2 (congruency) ANOVA with OSPAN as a between subject factor was conducted. We found a main effect of load [*F* (1, 90) = 105.125; *p < 0.0001*], and a main effect of congruency [*F* (1, 90) = 81.185; *P < 0.0001*]. We also found a significant congruency by OSPAN interaction [*F* (1, 90) = 8.969; *p < 0.004*], which indicated that those with higher OSPAN scores experience significantly less interference overall. There were no other significant interactions. Following that, we performed another median split of the data, this time based on SSPAN scores (n=46). We ran a 2 (condition) x 2 (congruency) ANOVA with SSPAN as a between subject factor. We observed a main effect of load [*F* (1, 90) = 104.2; $P < 0.0001$], and congruency [*F* (1, 90) =75.877; $p < 0.0001$]. There was also a congruency by SSPAN interaction [*F* (1, 90) = 6.978; $p < 0.01$], which indicated that those with higher SSPAN score experience significantly less interference overall. There were no other significant interactions.

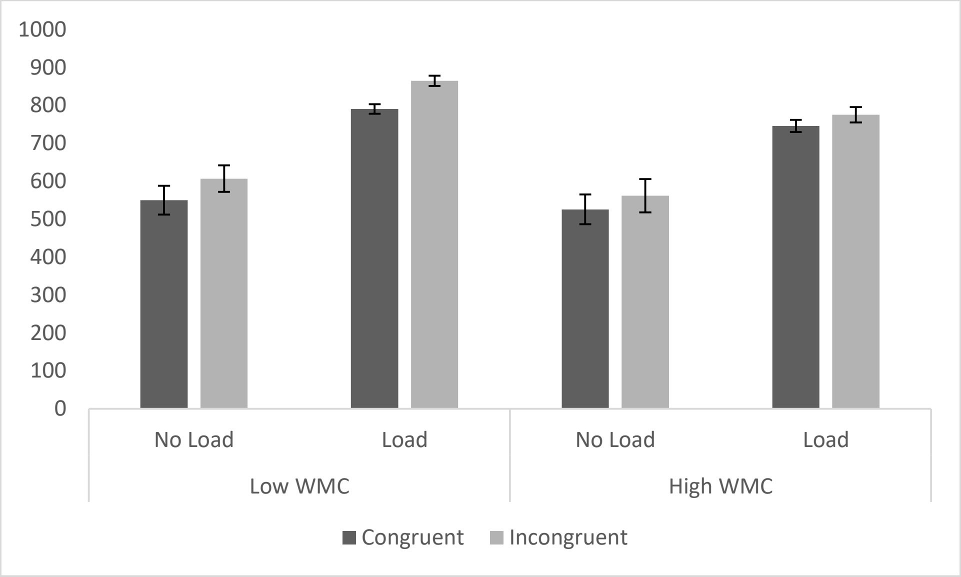

Figure 7.3: Median split by OSPAN scores. Response times to the Stroop task as a function of working memory capacity and load condition.

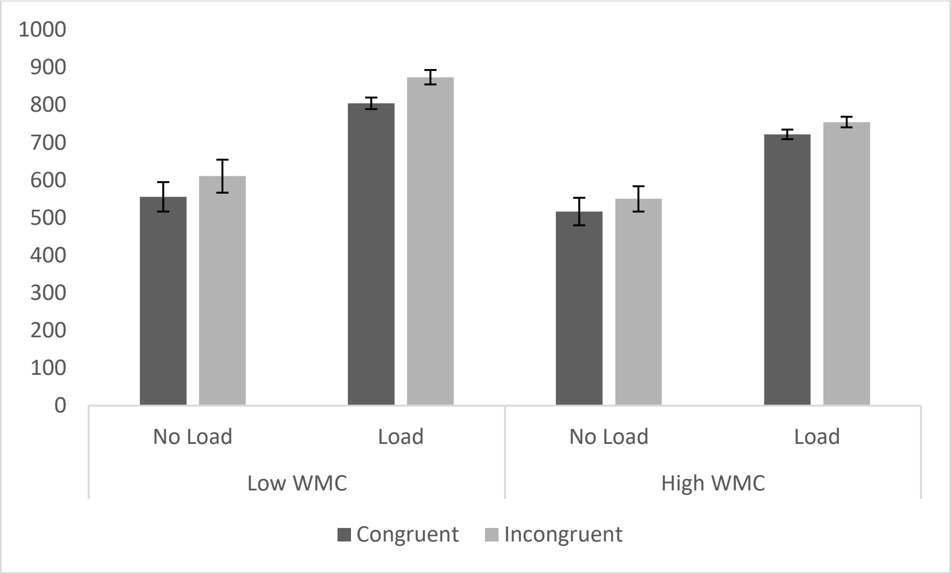

Figure 7.4: Median split by SSPAN scores. Response times to the Stroop task as a function of working memory capacity and load condition.

Discussion

In the analysis of accuracy, it was found that participants were less accurate in the incongruent conditions than the congruent conditions, indicative of interference. Participants were also equally accurate in the Stroop task whether or not they were maintaining a load. This could just indicate that when considering accuracy, this paradigm is not sensitive enough to elicit individual differences in accuracy overall. This led us to do a median split based upon the span scores. When we conducted a median split by OSPAN, we found that participants with higher OSPAN scores were more accurate and experienced less interference than participants with lower OSPAN scores. A median split by SSPAN then also indicated that participants with higher SSPAN scores were more accurate and experienced less interference than participants with lower SSPAN scores. The fact that there is no difference in terms of the prediction of accuracy performance by each span score supports the controlled attention account that these measures are domain-general measures of working memory not sensitive to domain-specific information.

We then analyzed probe accuracy to see whether either span score was a better predictor of working memory performance. The controlled attention account would say that each span score would not differ in ability to predict performance. However, the multiple component approach would say that ability to predict performance would vary by whether the informational domain of the span score matched the load type of the working memory task. While both span scores were positively correlated with probe performance, when controlling for each span score in the model, it was found that although the difference between the correlations was not statistically different OSPAN tended to be a better predictor than SSPAN. This is particularly evident that when controlling for OSPAN, the strength of the relationship between SSPAN and probe accuracy weakened. This is a trend that supports the multiple component approach as the verbal informational domain of the OSPAN matched the verbal working memory load of the task.

An RT analysis was then conducted. We first checked for the pattern of interference effects and found that load increased interference overall. A finding that supports both accounts. We then conducted a median split to determine whether or not performance varied by span score. We found that both higher OSPAN and SSPAN scores predicted less interference and did not differ in terms of the pattern of interference effects observed. This finding supports the controlled attention claim that both span scores would be not differ in their prediction of performance.

Chapter 8: Experiment 2

Methods

Experiment 2 used a spatial load and a verbal target. In the Stroop component, participants were required to identify the target word ‘LEFT’ or ‘RIGHT’, while ignoring the orientation of a distractor arrow which could be pointing left or right. In the working memory load condition, participants had to maintain the location of 4 squares while performing the Stroop task. They then had to indicate whether or not a presented square was part of the previous set. Here, the target required verbal processing, while the load required spatial processing.

According to the multiple component approach, we would expect to see a decrease in interference as the spatial load reduces the capacity for the processing of the spatial distractor. Here the symmetry span would be significantly more predictive of performance than the operation span as it is testing the capacity of the spatial component of the working memory system. According to the controlled attention account, we would expect to see an increase in interference in the Stroop task in the load condition compared to the no-load condition regardless of load type. Both the operation span and symmetry span scores would be equally predictive of performance. In terms of probe accuracy, the multiple component model would predict that the symmetry span would be a better predictor of recall of the spatial working memory load than the symmetry span. The controlled attention approach would not predict that there would be a significant difference in terms of the amount of variance each span accounts for.

Participants. Participants were 105 undergraduate students at The George Washington University. All subjects had healthy and normal or corrected to normal vision. They will receive class credit for participation.

Stimulus, Procedure, and Design. Experiment 2 used the exact same stimuli and conditions in the Stroop condition as Experiment 1. Here, the difference pertained to the spatial working memory load. Participants had to remember the location of 4 different squares. After performing the Stroop task they had to recall if the presented square was part of the memory set (figure 6.1). The procedure for Experiment 2 was exactly the same as Experiment 1, apart from the use of the spatial working memory load. There was a practice block of 20 trials. A single-task block or dual-task block of 64 trials each followed. The order of these blocks was randomly selected after the practice block. The resulting experimental design of Experiment 2 was a (2) Condition × (2) Congruency design, with span as a between participants variable.

Results

Outlier exclusion. First, a trial by trial analysis was conducted for each participant. Any trial with an RT below 200ms or above 2000ms in the Stroop task was excluded. All participants who achieved a mean RT of more than 2.5 standard deviations for the Stroop task were excluded from all RT and accuracy analysis. For the RT analysis of the Stroop task, in the load condition, only the trials in which the participant was accurate in the probe, were included in analysis. All participants who achieved a mean accuracy of equal to or below 50% for the working memory probe, (performance equal to chance), were excluded from all RT and accuracy analyses. Only participants who completed all tasks (Stroop, OSPAN, and SSPAN) were included. A total of 28 participants were excluded according to these criteria (n=77).

Accuracy. In the no-load condition, Stroop task mean accuracy was 97% compared to a mean accuracy of 99% for the Stroop task in the load condition. A 2 (condition) x 2 (congruency) ANOVA was run. There was a main effect of load [F (1, 76) = 31.27; $p > 0.0001$], and there was a main effect of congruency [F (1, 76) = 15.3; $p < 0.0001$]. This indicated that participants were more accurate in the load condition overall, but less accurate in the incongruent conditions. There was no interaction between load and congruency [F (1, 92) = .110; $p > 0.05$] indicating that there was not a significant change in accuracy as a function of load.

We then did a median split based upon OSPAN scores. When including OSPAN as a between subject factor, we observed a main effect of load [F (1, 74) = 33.815; $p < 0.0001$] and a main effect of congruency [F (1, 74) = 13.749; $p < 0.0001$]. We also saw a significant interaction between load and OSPAN [F (1, 74) = 8.812; $p < 0.004$], which indicated that those with higher OSPAN scores are more accurate, specifically in the no-load condition (98% vs 96%). When including SSPAN as a between subject factor, we observed a main effect of load [F (1, 74) = 34.308; $p < 0.0001$] and a main effect of congruency [F (1, 74) = 7.849; $p < 0.006$]. There were no significant interactions. However, the OSPAN and SSPAN only differed in their predicted performance in the no-load condition and a paired sample t-test revealed this difference to be non-significant [$t = -.873$, $p > 0.05$, df=37].

Probe Accuracy. Mean accuracy for the spatial working memory probe was 68%. Correlation analyses were conducted on the relationship between OSPAN, SSPAN, and probe accuracy. We tested the relationship between OPSAN and SSPAN and found a significant positive correlation [r =.446; p <0.0001; n=77]. When then modeled the span scores on probe accuracy independently. The OSPAN score significantly predicted accurate recall [r =.199; p < 0.042; n=77]. The SSPAN also significantly predicted accurate recall [r =.44; p <0.0001; n=77]. These correlations were statistically different from each other [z = 1.78, p < 0.04]. As the OSPAN, SSPAN and probe accuracy were all significantly correlated, we ran two partial correlations. First we ran a partial correlation to better identify the relationship between probe accuracy and the two span scores. When controlling for SSPAN in the model, OSPAN did not significantly correlate with probe accuracy [r=.003; p > 0.05; df=74]. However, when controlling for OSPAN in the model, SSPAN demonstrated a much stronger positive correlation than OSPAN [r=.400; p < 0.0001; df=74]. Again, these correlations were significantly different [z = 12.53, p < 0.01]

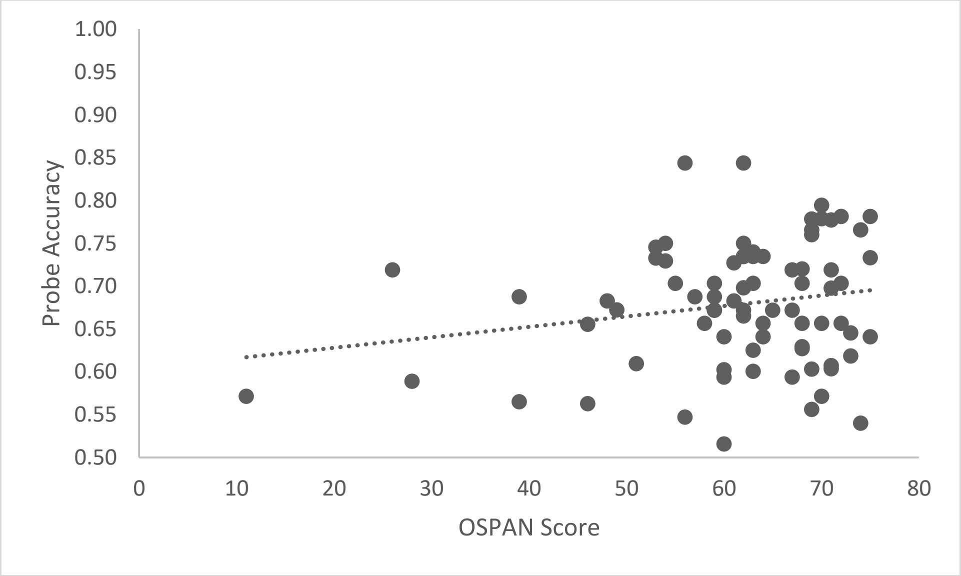

Figure 8.1: Scatterplot showing the relationship between probe accuracy and participant OSPAN scores.

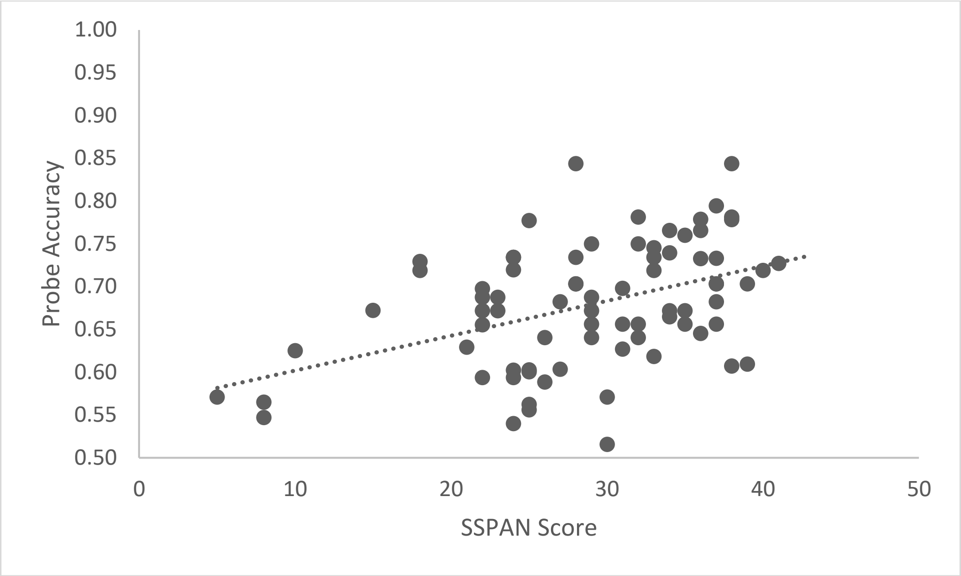

Figure 8.2: Scatterplot showing the relationship between probe accuracy and participant SSPAN scores.

Response Times. We first ran a 2 (condition) x 2 (congruency) ANOVA to check for interference patterns. We found a main effect of load [*F* (1, 76) = 160.441; $p < 0.0001$], indicating that participants were overall slower in the load condition. We also found a main effect of congruency [*F* (1, 76) = 32.33; $p < 0.0001$]. There was no significant interaction between load and congruency.

We then performed a median split of the data based on OSPAN scores (n=38 per group). A 2 (condition) x 2 (congruency) ANOVA with OSPAN as a between subject factor was conducted. We found a main effect of load [*F* (1, 74) = 155.718; $p < 0.0001$], and a main effect of congruency [*F* (1, 74) = 34.182; $p < 0.0001$]. We did not find a significant congruency by OSPAN interaction [*F* (1, 74) = 3.086; $p > 0.05$]. Following that, we performed another median split of the data, this time based on SSPAN scores (n=38). We ran a 2 (condition) x 2 (congruency) ANOVA with SSPAN as a between subject factor. We observed a main effect of load [F (1, 74) = 154.275; $p < 0.0001$], and congruency [F (1, 74) =32.041; $p < 0.0001$]. We did not find a significant congruency by SSPAN interaction [F (1, 74) = 1.168; $p > 0.05$]. There were no other significant interactions.

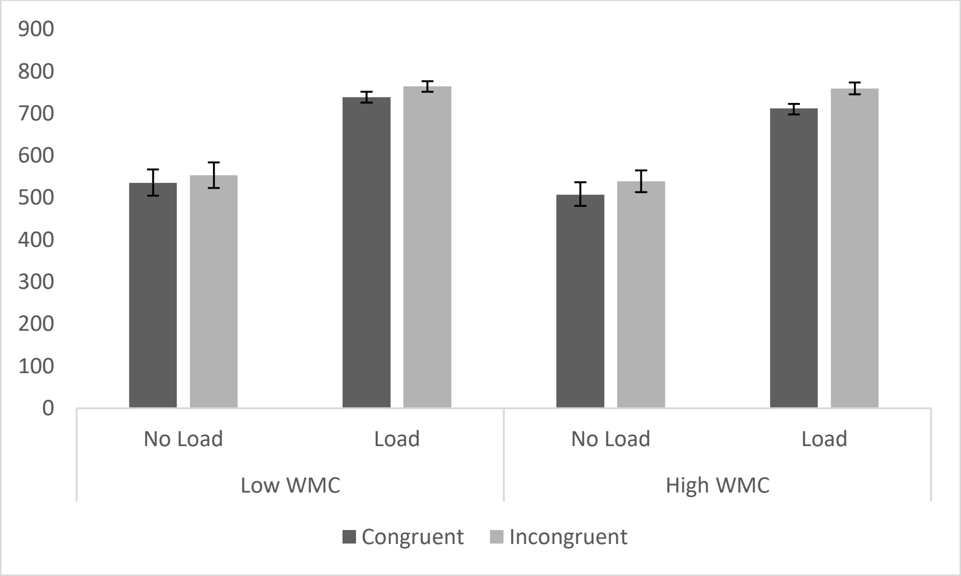

Figure 8.3: Median split by OSPAN scores. Response times to the Stroop task as a function of working memory capacity and load condition.

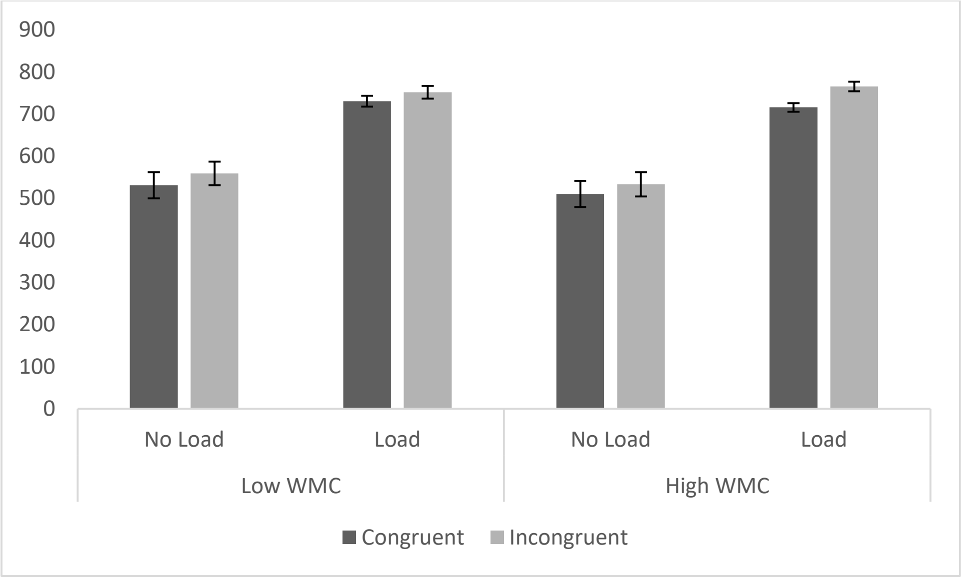

Figure 8.4: Median split by SSPAN scores. Response times to the Stroop task as a function of working memory capacity and load condition.

Discussion

In the analysis of accuracy, it was found that participants were less accurate in the incongruent conditions than the congruent conditions, indicative of interference. Participants were also more accurate in the Stroop task when maintaining a load. This could indicate a speed accuracy trade off. A median split based upon the span scores revealed that when split by OSPAN, we found that participants with higher OSPAN scores were more accurate and experienced less interference than participants with lower OSPAN scores, in the load condition. A median split by SSPAN failed to indicate that participants with higher SSPAN scores were more accurate and experienced less interference than participants with lower SSPAN scores. While at face value this would seem to support the multiple component model, the difference in predicted performance was 1% between the OSPAN and SSPAN scores for the high span individuals and this was not significant.

We then analyzed probe accuracy to see whether either span score was a better predictor of working memory performance. The controlled attention account would say that each span score would not differ in ability to predict performance. However, the multiple component approach would say that ability to predict performance would vary by whether the informational domain of the span score matched the load type of the working memory task. While both span scores were positively correlated with probe performance, SSPAN demonstrated a stronger relationship with probe accuracy. When controlling for SSPAN span in the model, it was found that the OSPAN failed to predict performance. Controlling for OSPAN did not change the predictive power of the SSPAN in predicting probe performance. This is a finding that supports the multiple component model as the spatial informational domain of the SSPAN matched the spatial working memory load of the task.

An RT analysis was then conducted. We first checked for the pattern of interference effects and found that load increased interference overall. This is contrary to the prediction of the multiple component approach which would predict diminished interference (compared to Exp 1) as a result of the spatial load matching the spatial distractor. We then conducted a median split to determine whether or not performance varied by span score. We found that both higher OSPAN and SSPAN scores did not predict less interference compared to low span individuals. Further they did not differ in terms of the prediction of the pattern of interference effects observed (load compared to no-load). This finding supports the controlled attention claim that both span scores would not differ in their prediction of performance.

Chapter 9: Experiment 3

Methods

Both experiment 1 and 2 made use of a verbal target. Experiment 3 made use of a spatial target and a verbal distractor. The stimuli and design of the Stroop component of Experiment 3 were exactly the same as Experiments 1 and 2, except participants were told to respond to the orientations of the target arrow, while ignoring the verbal distractor. Experiment 3 used the same spatial working memory load as Experiment 2. Here, both the target and the working memory load required spatial processing.

According to the multiple component approach, we would expect to see a decrease in increase in interference as the spatial load reduces the capacity for the processing of the spatial target. Here the symmetry span would be significantly more predictive of performance than the operation span as it is testing the capacity of the spatial component of the working memory system. According to the controlled attention account, we would expect to see an increase in interference in the Stroop task in the load condition compared to the no-load condition regardless of load type. Both the operation span and symmetry span scores would be equally predictive of performance. In terms of probe accuracy, the multiple component model would predict that the symmetry span would be a better predictor of recall of the spatial working memory load than the symmetry span. The controlled attention approach would not predict that there would be a significant difference in terms of the amount of variance each span accounts for.

Participants. Participants were 82 undergraduate students at Penn State University. All participants had healthy and normal or corrected to normal vision. They received class credit for participation.

Stimulus, Procedure, and Design. Experiment 3 used the exact same stimuli in the Stroop condition as Experiment 1 and 2. Here, the difference pertained to the use of the arrow as a spatial target. The verbal distractor was the word ‘LEFT’ or ‘RIGHT’. If the arrow was pointing left participants had to respond with the ‘s’ key, while if the arrow was pointing right, participants had to respond with the ‘l’ key. The spatial working memory load was the same as Experiment 2. Participants were also required to remember the location of 4 different squares. After performing the Stroop task, they had to recall if the presented square was part of the memory set (figure 6.2). If it was they responded with the ‘p’ key. If it was not, they responded with the ‘q’ key. The procedure for Experiment 3 was exactly the same as Experiment 2, apart from the use of the target arrow. There was a practice block of 20 trials. A single-task block or dual-task block of 64 trials each followed. The order of these blocks was randomly selected after the practice block. The resulting experimental design of Experiment 3 was a (2) Condition × (2) Congruency design, with span as a between participants variable.

Results

Outlier exclusion. First, a trial by trial analysis was conducted for each participant. Any trial with an RT below 200ms or above 2000ms in the Stroop task was excluded. All participants who achieved a mean RT of more than 2.5 standard deviations for the Stroop task were excluded from all RT and accuracy analysis. For the RT analysis of the Stroop task, in the load condition, only the trials in which the participant was accurate in the probe, were included in analysis. All participants who achieved a mean accuracy of equal to or below 50% for the working memory probe, (performance equal to chance), were excluded from all RT and accuracy analyses. Only participants who completed the tasks (Stroop task, OSPAN, and SSPAN) were included. A total of 4 participants were excluded according to these criteria (n=78).

Accuracy. In the no-load condition Stroop task mean accuracy was 98% compared to a mean accuracy of 100% for the Stroop task in the load condition. A 2 (condition) x 2 (congruency) ANOVA was run. There was a main effect of load [F (1, 77) = 50.287; $p > 0.0001$], and there was a main effect of congruency [F (1, 77) = 5.324; $p < 0.024$]. This indicated that participants were more accurate in the load condition overall, but less accurate in the incongruent conditions. There was no interaction between load and congruency [F (1, 77) = .893; $p > 0.05$] indicating that there was not a significant change in accuracy as a function of load.

We then did a median split based upon OSPAN scores. When including OSPAN as a between subject factor, we observed a main effect of load [F (1, 76) = 49.977; $p < 0.0001$] and a main effect of congruency [F (1, 76) = 5.338; $p < 0.0001$]. We saw no significant interaction between load and OSPAN [F (1, 76) = 1.203; $p > 0.05$]. When including SSPAN as a between subject factor, we observed a main effect of load [F (1, 76) = 49.634; $p < 0.0001$] and a main effect of congruency load [F (1, 76) = 5.258; $p < 0.025$]. There were no significant interactions.

Probe Accuracy. Mean accuracy for the spatial working memory probe was 71%. Correlation analyses were conducted on the relationship between OSPAN, SSPAN, and probe accuracy. We tested the relationship between OPSAN and SSPAN and found a significant correlation [r =.341; p <0.001; n=78]. When then modeled the span scores on probe accuracy independently. The OSPAN score failed to significantly predict accurate recall [r =.073; p > 0.05; n=78]. The SSPAN significantly predicted recall [r=.362; p

<0.001; n=78]. These correlations were statistically different from each other [$z = -1.87$, $p < 0.03$]. As the OSPAN, SSPAN and probe accuracy are not all significantly correlated, we could not run a partial correlation analysis. Thus, we ran a multiple regression model with OSPAN and SSPAN as the IV's and probe accuracy as the DV. The overall model was significant [$R^2 = .134$, $F(2, 75) = 5.802$, $p < .005$]. The SSPAN score was positively and significantly correlated with probe accuracy after controlling for OSPAN in the model [$t = 3.338$, $p < 0.001$]. When controlling for SSPAN, OSPAN scores failed to predict probe accuracy and did not contribute significantly to the model [$t = -.499$, $p > 0.05$].

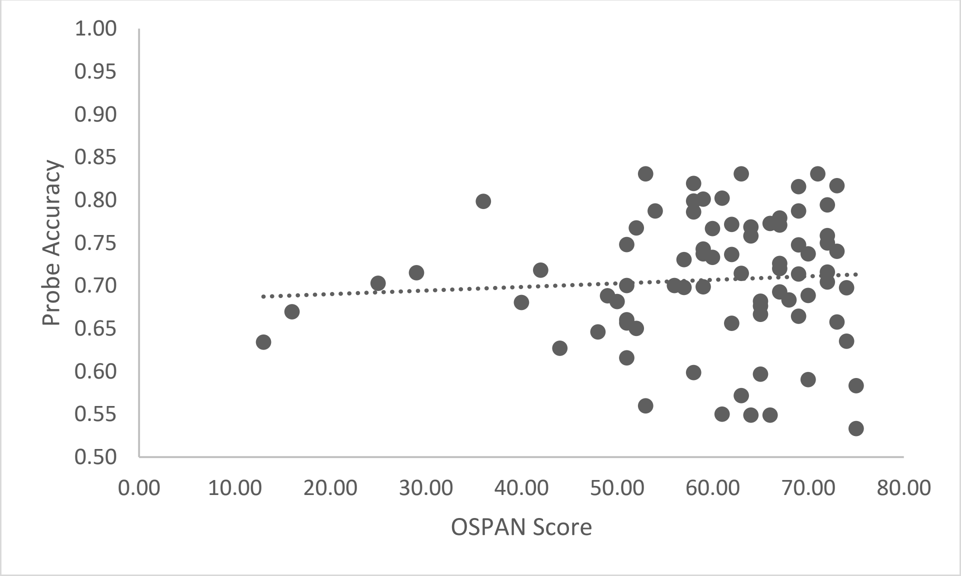

Figure 9.1: Scatterplot showing the relationship between probe accuracy and OSPAN scores.

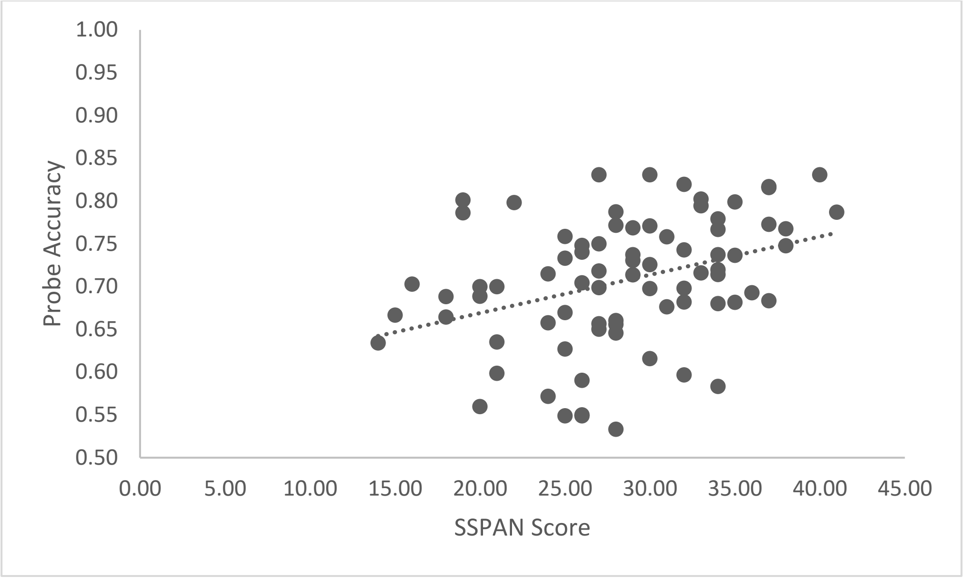

Figure 9.2: Scatterplot showing the relationship between probe accuracy and SSPAN scores.

Response Times. We first ran a 2 (condition) x 2 (congruency) ANOVA to check interference patterns. We found a main effect of load [F (1, 77) = 164.361; $p < 0.0001$], indicating that participants were overall slower in the load condition. We also found a main effect of congruency [F (1, 77) = 27.422; $p < 0.0001$]. We also found a significant interaction between load and congruency [F (1, 77) = 13.755; $p < 0.0001$], indicating greater interference in the load condition. This is most likely driven by the lack of interference effects in the no-load condition.

We then performed a median split of the data based on OSPAN scores (n=39 per group). A 2 (condition) x 2 (congruency) ANOVA with OSPAN as a between subject factor was conducted. We found a main effect of load [F (1, 76) = 172.721; $p < 0.0001$], and a main effect of congruency [F (1, 76) = 27.108; $p < 0.0001$]. We also found a significant congruency by OSPAN interaction [F (1, 76) = 4.917; $p < 0.03$] indicating that high OSPAN scores led to larger interference effects, particularly in the load condition (high span = 48ms vs low span = 33ms). There was also a load by congruency interaction [*F* (1, 76) = 13.822; $p < 0.0001$], indicating interference effects were greater in the load condition than no-load condition. There were no other significant interactions. Following that, we performed another median split of the data, this time based on SSPAN scores (n=38). We ran a 2 (condition) x 2 (congruency) ANOVA with SSPAN as a between subject factor. We observed a main effect of load [*F* (1, 76) = 169.215; $p < 0.0001$], and congruency [*F* (1, 74) =27.874; $p < 0.0001$]. We also found a load by congruency interaction [*F* (1, 76) = 13.724; $p < 0.0001$] indicating that interference effects increased in the load condition. We did not find a significant load by SSPAN interaction although it was near significance [*F* (1, 76) = 3.274; $p < 0.074$]. However, we did find that a high SSPAN predicted improved performance in the load condition for high span individuals (30 ms) vs. low span individuals (51 ms). It must be noted however, that the amount of interference predicted by each span score in the load condition did not differ by span type (SSPAN vs OSPAN) or span score (High vs Low).

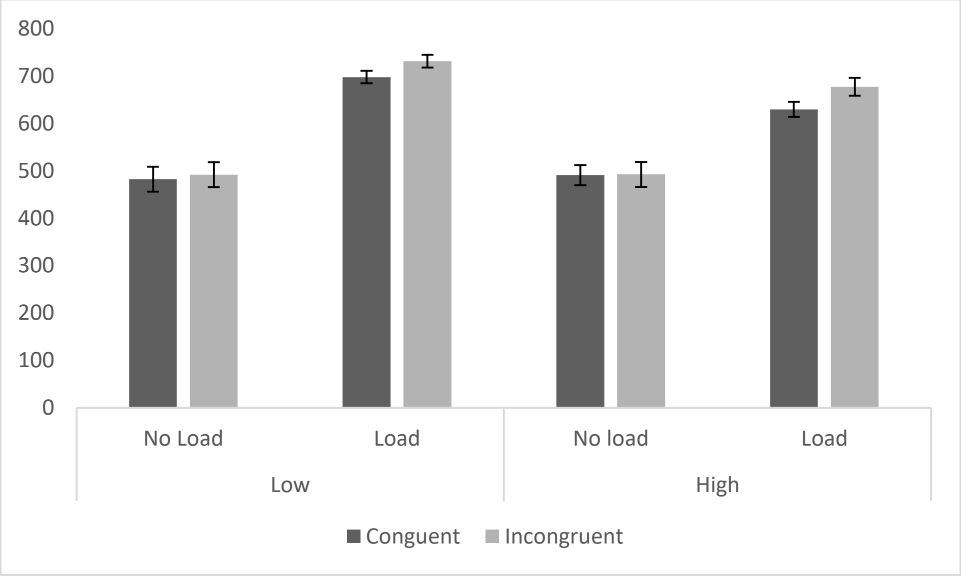

Figure 9.3: Median split by OSPAN scores. Response times to the Stroop task as a function of working memory capacity and load condition.

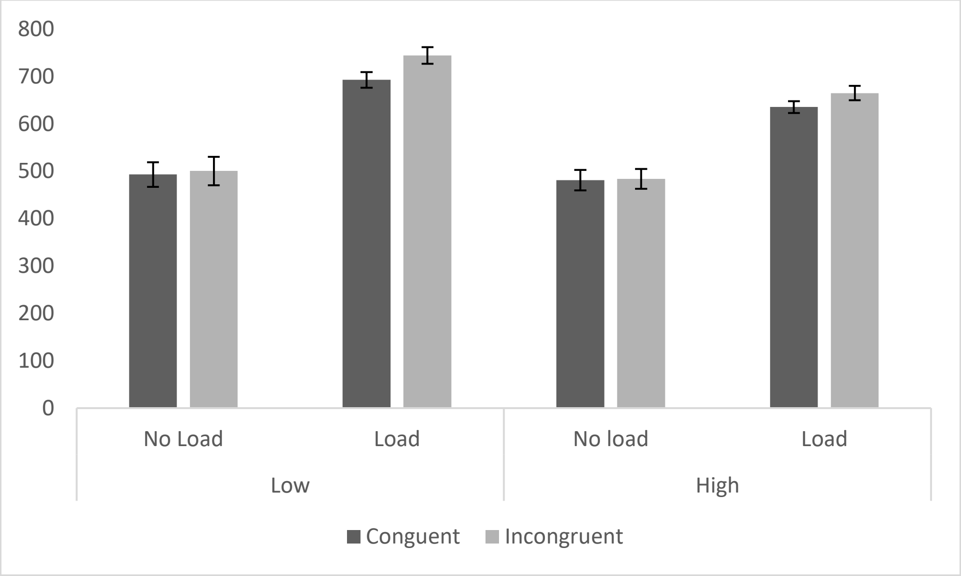

Figure 9.4: Median split by SSPAN scores. Response times to the Stroop task as a function of working memory capacity and load condition.

Discussion

In the analysis of accuracy, it was found that participants were less accurate in the incongruent conditions than the congruent conditions, indicative of interference.

Participants again more accurate in the Stroop task when maintaining a load. This could indicate a speed accuracy trade off. A median split revealed that neither span scores significantly predicted Stroop performance.

We then analyzed probe accuracy to see whether either span score was a better predictor of working memory performance. The controlled attention account would say that each span score would not differ in ability to predict performance. However, the multiple component approach would say that ability to predict performance would vary by whether the informational domain of the span score matched the load type of the working memory task. It was found that while both the OSPAN score and SSPAN scores were correlated, only the SSPAN was significantly correlated with probe accuracy. While both span scores were positively correlated with probe performance, when controlling for SSPAN span score in the model, it was found that the OSPAN failed to predict performance. Controlling for OSPAN did not change the predictive power of the SSPAN in predicting probe performance. This is a finding that supports the multiple component approach as the spatial informational domain of the SSPAN matched the spatial working memory load of the task.

An RT analysis was then conducted. We first checked for the pattern of interference effects and found that load increased interference overall, consistent with both accounts. We then conducted a median split to determine whether or not predicted performance varied by span score. We found that higher OSPAN scores predicted more interference compared to low span individuals. Conversely, higher SSPAN scores predicted smaller interference effects in the load condition. However it is important to note that both high and low span individuals in each span split, experienced significant interference. Further the amount of interference predicted in the load condition, by each span score did not differ. Thus, it is reasonable to assume the neither the SSPAN or OSPAN are better predictors of performance in the Stroop task. This finding again supports the controlled attention model.

Chapter 10: Experiment 4

Like Experiment 3, Experiment 4 made use of a spatial target and a verbal distractor. The stimuli and design of the Stroop component of Experiment 4 was the same as Experiment 3. Experiment 4 used the same verbal working memory load as Experiment 1. Here, the target required spatial processing while the working memory load required verbal processing.

According to the multiple component approach, we would expect to see a decrease in interference as the verbal load reduces the capacity for the processing of the verbal distractor. Here the operation span would be significantly more predictive of performance than the symmetry span as it is testing the capacity of the spatial component of the working memory system. According to the controlled attention account, we would expect to see an increase in interference in the Stroop task in the load condition compared to the no-load condition regardless of load type. Both the operation span and symmetry span scores would be equally predictive of performance. In terms of probe accuracy, the multiple component model would predict that the operation span would be a better predictor of recall of the verbal working memory load than the symmetry span. The controlled attention approach would not predict that there would be a significant difference in terms of the amount of variance each span accounts for.

Participants. Participants were 95 Master level Amazon Turk workers. Turk workers achieve a Masters distinction by consistently completing HITs of a certain type with a high degree of accuracy across a variety of Requesters. They received financial compensation for participation ($8/h).

Stimulus, Procedure, and Design. Experiment 4 used the exact same stimuli in the Stroop condition as Experiment 3. The verbal distractor was the word 'LEFT' or 'RIGHT'. If the arrow was pointing left participants had to respond with the 's' key, while if the arrow was pointing right, participants had to respond with the 'l' key. The working memory load was the same as Experiment 1. Participants were also required to remember the identity of a set of 7 letters. After performing the Stroop task, they had to recall if the presented letter was part of the memory set (figure 6.2). If it was, they responded with the 'p' key. If it was not, they responded with the 'q' key. The procedure for Experiment 4 was exactly the same as Experiment 3, apart from the use of the verbal working memory load. There was a practice block of 20 trials. A single-task block or dual-task block of 64 trials each followed. The order of these blocks was randomly selected after the practice block. The resulting experimental design of experiment 4 was a (2) Condition × (2) Congruency design, with span as a between participants variable.

Results

Outlier exclusion. First, a trial by trial analysis was conducted for each participant. Any trial with an RT below 200ms or above 2000ms in the Stroop task was excluded. All participants who achieved a mean RT of more than 2.5 standard deviations for the Stroop task were excluded from all RT and accuracy analysis. For the RT analysis of the Stroop task, in the load condition, only the trials in which the participant was accurate in the probe, were included in analysis. All participants who achieved a mean accuracy of equal to or below 50% for the working memory probe, (performance equal to chance), were excluded from all RT and accuracy analyses. Only participants who completed all tasks (Stroop, OSPAN, and SSPAN) were included. A total of 13 participants were excluded according to these criteria (n=82).

Accuracy. In the no-load condition Stroop task mean accuracy was 99% compared to a mean accuracy of 99% for the Stroop task in the load condition. A 2 (condition) x 2 (congruency) ANOVA was run. There were no main effects of load [F (1, 75) = 1.996; $p > 0.05$], or congruency [F (1, 75) = 2.128; $p > 0.05$]. There was no significant load by congruency interaction, [F (1, 75) = 0.019; $p > 0.05$.]

We then did a median split based upon OSPAN scores. When including OSPAN as a between subject factor, we failed to observe a main effect of load [F (1, 74) = 1.978; $p > 0.05$], or a main effect of congruency [F (1, 74) = 2.104; $p > 0.05$]. There were no significant interactions. When including SSPAN as a between subject factor, we failed to observe a main effect of load [F (1, 74) = 2.162; $p > 0.05$] or a main effect of congruency load [F (1, 74) = 1.057; $p > 0.05$]. There were no significant interactions.

Probe Accuracy. Mean accuracy for the spatial working memory probe was 76%. Correlation analyses were conducted on the relationship between OSPAN, SSPAN, and probe accuracy. We tested the relationship between OPSAN and SSPAN and found a significant correlation [r =.347; p < 0.01; n=76]. We then modeled the span scores on probe accuracy independently. The OSPAN score significantly predict accurate recall [r =.349; p < 0.001; n=76]. The SSPAN also significantly predicted recall [r =.200; p < 0.042; n=76]. These correlations were not statistically different. As the OSPAN, SSPAN and probe accuracy were all significantly correlated, we ran a partial correlation analysis to better identify the relationship between probe accuracy and the two span scores. When controlling for SSPAN in the model, OSPAN significantly correlated with probe accuracy [r =.304; $p < 0.004$, df=73]. However, when controlling for OSPAN in the model, SSPAN failed to show a significant relationship with probe accuracy, [r =.089; $p > 0.05$, df=73]. These correlations were significantly different [$z = 1.67$, $p < 0.05$].

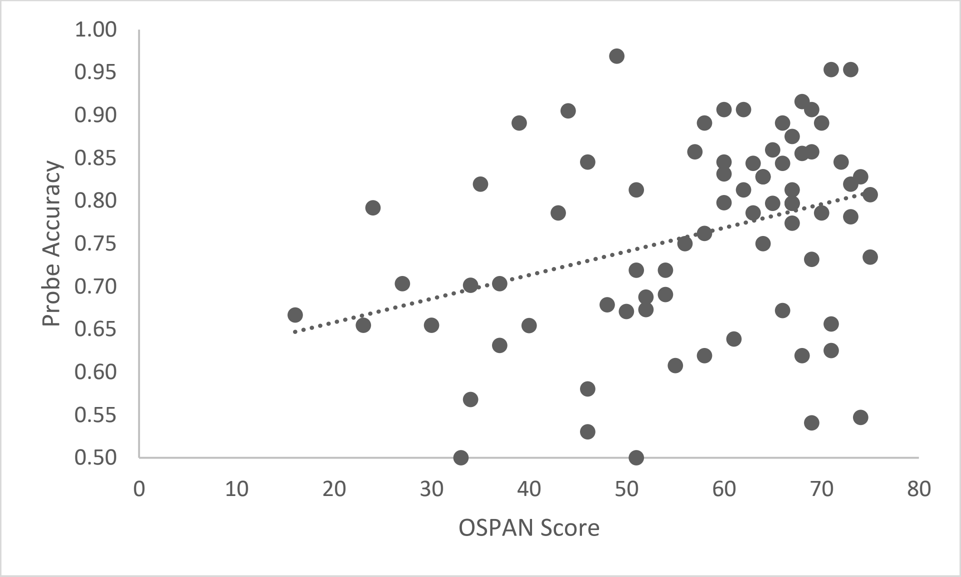

Figure 10.1: Scatterplot showing the relationship between probe accuracy and OSPAN scores.

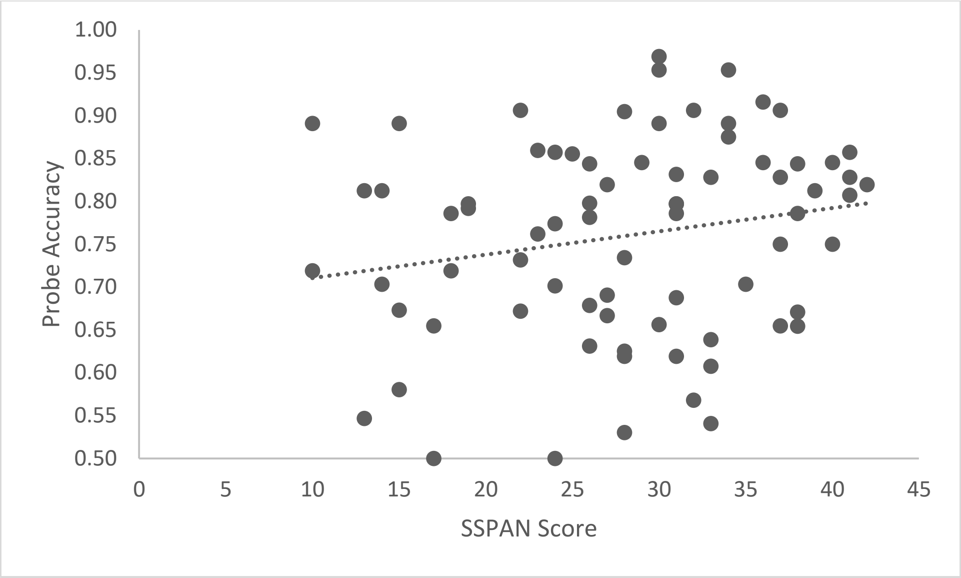

Figure 10.2: Scatterplot showing the relationship between probe accuracy and SSPAN scores.

Response Times. We first ran a 2 (condition) x 2 (congruency) ANOVA to check interference patterns. We found a main effect of load [*F* (1, 75) = 21.232; $p < 0.0001$], indicating that participants were overall slower in the load condition. We also found a main effect of congruency [*F* (1, 75) = 9.705; $P < 0.003$]. The interaction between load and congruency was near significant [*F* (1, 75) =3.491; $P < 0.066$]. Like the previous experiments, this is most likely driven by the lack of interference effects in the no-load condition.

We then performed a median split of the data based on OSPAN scores (n=38 per group). A 2 (condition) x 2 (congruency) ANOVA with OSPAN as a between subject factor was conducted. We found a main effect of load [*F* (1, 74) = 21.046; $p < 0.0001$], and a main effect of congruency [*F* (1, 74) = 10.002; $p < 0.002$]. There was a OSPAN by congruency interaction that was near significance [*F* (1, 74) = 3.292; $p < 0.074$], as well as a near significant load by congruency interaction, [*F* (1, 74) = 3.447; $p < 0.067$]. There were no other significant correlations.

Following that, we performed another median split of the data, this time based on SSPAN scores (n=38). We ran a 2 (condition) x 2 (congruency) ANOVA with SSPAN as a between subject factor. We observed a main effect of load [*F* (1, 74) = 21.093; $p < 0.0001$], and congruency [*F* (1, 74) = 10.091; $p < 0.002$]. We also found a SSPAN by congruency interaction [*F* (1, 74) = 3.983; $p < 0.05$] indicating that participants with high span scores experience lower interference effects overall. A load by congruency interaction was found to be near significance [*F* (1, 74) = 3.447; $p < 0.067$]. There were no other significant interactions. As the load by congruency interaction is of most interest of difference between the two span scores, we compared the observed interference patterns by span score (Table 3), and they were not found to be significantly different.

Table 3

Experiment 4: Interference effects in the Stroop task as predicted each span score.

WMC	Condition	SSPAN	OSPAN
High WMC	No-load	13 ms	13 ms
	Load	25 ms	24 ms
Low WMC	No-load	-3 ms	-2 ms
	Load	12 ms	12 ms

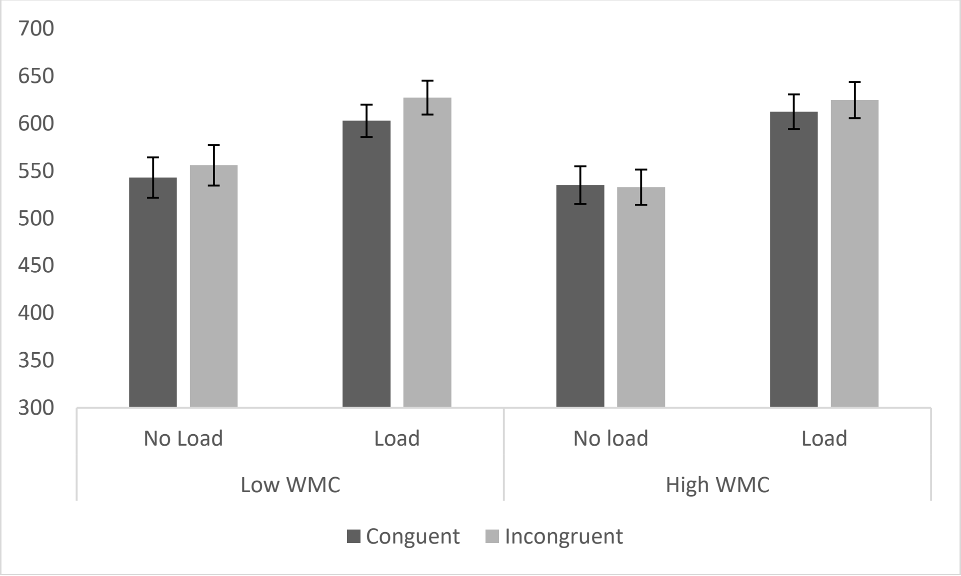

Figure 10.3: Median split by OSPAN scores. Response times to the Stroop task as a function of working memory capacity and load condition.

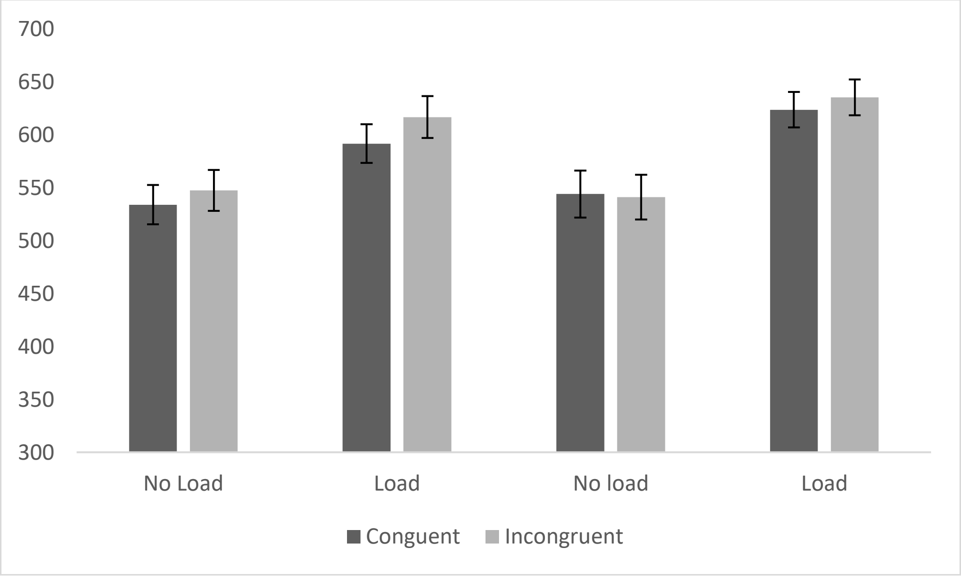

Figure 10.4: Median split by SSPAN scores. Response times to the Stroop task as a function of working memory capacity and load condition.

Discussion

In the analysis of accuracy, it was found that participants were less accurate in the incongruent conditions than the congruent conditions, indicative of interference. Participants did not differ in the no-load conditions compared to the load conditions. A median split revealed that neither span scores significantly predicted Stroop accuracy.

We then analyzed probe accuracy to see whether either span score was a better predictor of working memory performance. The controlled attention account would say that each span score would not differ in ability to predict performance. However, the multiple component approach would say that ability to predict performance would vary by whether the informational domain of the span score matched the load type of the working memory task. It was found that while both the OSPAN score and SSPAN scores were correlated, only the SSPAN was significantly correlated with probe accuracy. While both span scores were positively correlated with probe performance, when controlling for OSPAN span score in the model, it was found that the OSPAN failed to predict performance. Controlling for OSPAN did not change the relationship between SSPAN and probe performance. This is a finding that supports the multiple component approach as the verbal informational domain of the SSPAN matched the verbal working memory load of the task.

An RT analysis was then conducted. We first checked for the pattern of interference effects and found that load increased interference overall, consistent with the controlled attention account but not with the multiple component models. We then conducted a median split to determine whether or not predicted performance varied by span score. While as first glance the SSPAN seems to better predict less interference overall for high span individuals compared to low span individuals, it was found that the observed interference in the OSPAN group was not different (Table 3). Thus again, when considering interference as a function of span, neither the OSPAN nor SSPAN are more predictive, lending support to the controlled attention account.

Chapter 11: General Discussion

The above details a set of experiments that measured the presence or absence of domain-general and domain-specific effects in a working memory load paradigm. We also quantified the relative ability of operation and spatial span to predict variability in those effects across participants. Here we tested the predictions of both the multiple component model and the controlled attention approach. As predicted, both domain-general and domain-specific effects were observed.

The domain-specific effects were demonstrated by the fact that each span score better predicted performance on the tasks which taxed the same informational domain. This verbal-spatial distinction is what would be predicted by the multiple component model and supports previous findings of this effect. We found that probe accuracy was better predicted by the span score which matched each working memory load's informational domain. If the working memory load was spatial, the symmetry span task was a better predictor of performance. If the load wad verbal, then the operation span was a better predictor of performance. This is an important finding as complex span tasks are meant to be domain-general in nature and should not vary significantly in their prediction of performance across informational domains. Another interesting finding was that there was a much greater difference in prediction of performance with the spatial load, with the symmetry span accounting for far more variance. When the verbal load was used, the variance accounted for by the two span tasks was more similar. However the operation span was still superior in predicting performance of the verbal load overall.

The domain-general effects were observed in the general pattern of interference in the Stroop task, as predicted by the controlled attention approach. Specifically, the ability to reject distracting information is mediated by a domain-general control mechanism that is not especially sensitive to domain-specific processes. It was also found that when under load, individuals with high working memory capacity were better able to resist interference. This was regardless of whether performance was predicted by either the symmetry span or operation span. These findings support fMRI results that show improved recruitment of control regions of the brain by individuals with high working memory capacity, specifically when under load (Osaka et al., 2003; Osaka et al., 2004; Sohn et al., 2008).

These findings also failed to replicate those of Kim et al (2005) in that interference effects were not modulated by the overlap between load and target. This is not to say that domain-specific load effects did not occur, rather that they were not observed when domain-general control resources were required to perform a task in the face of distracting information. This finding is supported by a recent paper that also failed to replicated the results from Kim et al (2005), citing inadequate experimental power and sample sizes (de Liaño, Stablum, & Umiltà., 2016). By demonstrating both effects, the results we provide motivation for considering a conceptualization of working memory that is better able to account for the domain-general and domain-specific load effects observed in the literature.

A discussed in this dissertation, there is a disconnect between how these models conceptualize working memory and how working memory is most likely implemented in the brain. Multiple component models make use of intermediate short term stores to facilitate the interfacing of the central executive with long term memory. In that regard, they fail to account for how the control system interfaces with the more specific storage structures. Controlled attention models collapse the stores into long term memory, yet the interfacing problem with LTM remains. Thus these models do not convey a physiologically plausible account of working memory. Further the previous experiemnts have shown that both domain-specific and domain-general process can occur in the same paradigm. Thus it is useful to consider how this could be the case, given that both models fail to fully account for these results.

A more plausible approach would be a model based upon graded heirarchy that allows very specific information to be processed at an early stage, towards a more general/abstract manner of processing. Such an approach is not unprecedented and graded heirarchical models have been successfully used to model visual processing for decades (Hubel & Wiesel, 1962). A more modern conceptualization known as the HMAX model was proposed by Riesenhuber and Poggio (1999) and attempted to demonstrate the physiological feasibility of the graded heierachical models that had been proposed in the past. Figure 11.1 shows an implenetation of the HMAX model with regards to the processing and identification of a complex object (Riesenhuber and Poggio, 2002).

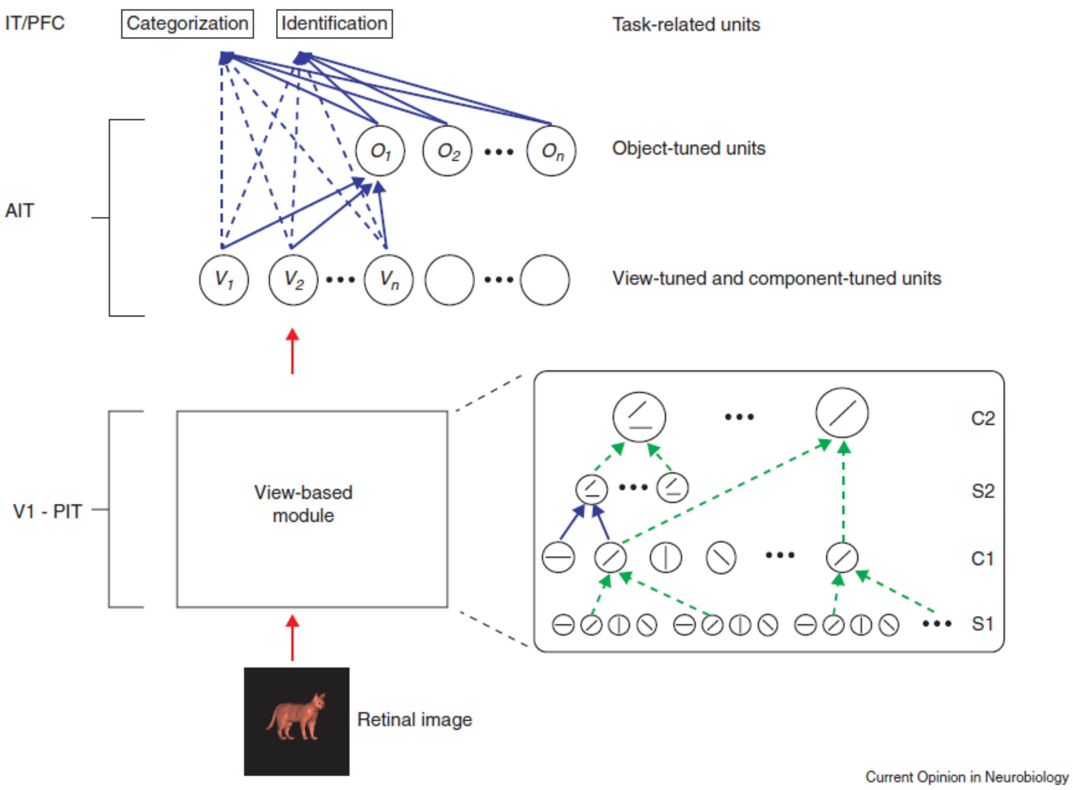

Figure 11.1: Model of the architecture of recognition in the cortex. The first layer in V1 represents linear oriented filters similar to simple cells; each unit in the next layer pools the outputs of simple cells of the same orientation but at slightly different positions (scales). Each of these units is still orientation selective but more invariant to position (scale), similarly to some complex cells. In the next stage, signals from complex cells with different orientations but similar positions are combined to create neurons (S2) tuned to a small dictionary of more complex features. The next layer is equivalent to complex cells in V1: by pooling together signals from S2, cells of the same type but at slightly different positions, the C2 units become more invariant to position (and scale) but preserve feature selectivity. They may correspond roughly to V4 cells. In the model, the C2 cells feed into view-tuned cells (Vn), with connection weights that are learned from exposure to a view of an object. The output of the view-based module is represented by view-tuned model units that exhibit tight tuning to rotation in depth (and other object-dependent transformations, such as illumination and facial expression) but are tolerant to scaling and translation of their preferred object view. Notice that the cells labeled here as view-tuned units, encompass, between the anterior IT (AIT) and posterior IT (PIT), a spectrum of tuning from views to complex features: depending on the synaptic weights determined during learning, each view-tuned cell becomes effectively connected to all or only a few of the units activated by the object view. The second part of the model starts with the view-tuned cells. Invariance to rotation in depth is obtained by combining, in a learning module, several view-tuned units tuned to different views of the same object, creating view invariant units (On). These, as well as the view-tuned units, can then serve as inputs to task modules that learn to perform different visual tasks such as identification/discrimination or object categorization. They consist of same generic learning but are trained with appropriate sets of examples to perform specific tasks. In addition to the feed-forward processing, there are likely feedback pathways for top-down modulation of neuronal responses throughout the processing hierarchy and to support the learning phase. All the units in the model represent single cells modeled as simplified neurons with modifiable synapses. Caption adapted from "Neural mechanisms of object recognition" by Riesenhuber and Poggio, *Current Opinion in Neurobiology, 12*, p. 163.

What is important about this model is that it matches up with the both physiology based and cognitive based models. It is able explain how highly domain-specific information such as line orientation can be fed through the system and integrated with other information to allow for complex object recognition. As indicated by the HMAX model, highly specific feature based processing occurs at V1 and the information is fed through the hierarchy to regions of the brain that are associated with later stage processing associated with the identification of the stimulus in IT/PFC. This provides evidence for a brain wide hierarchical network that can process both domain-specific and domain-general information in the same system. Thus, it should be possible to create a working memory model that incorporates this graded hierarchy between the control system and the domain-specific aspects of the system. This incorporation would go some way to explain how domain-specific information can be processed at the domain-general level, in the same system, in a physiologically plausible way. One could argue that the HMAX model works because of the physiological makeup of the visual system that supports graded hierarchical processing and that that may not be the case for more frontal regions.

In fact, such a hierarchy has been demonstrated in frontal cortex as an anterior-posterior gradient (for review see; Bunge, 2004). For example, Badre & D’Esposito (2007) found that goal representation becomes more abstract as you more forward along the anterior-posterior gradient. They used a series of nested tasks which were manipulated at varying levels of task abstraction. The simplest manipulated response competition which involved finger responses to colored squares. The next task added a layer of complexity by telling participants to respond to features. The following task added a dimension element where participants had to respond to both size and shape. The final task required participants to respond to context where the response mapping changed according to block. It was found that as the task became more complex, more anterior, prefrontal regions of the frontal cortex were recruited. When the task required only one level of abstraction (color identification) the premotor cortex was mainly recruited. Further, this is a true hierarchy in that damage to regions that support the lowest levels of the hierarchy (premotor regions) will result in deficits in performance in tasks that require greater abstraction (Badre, Hoffman, Cooney & D'Esposito, 2009).

The HMAX model demonstrates the possibility that hierarchical cognitive models can reflect the physiology of the brain. Further, a hierarchical organizational structure, at least to some extent is present in frontal cortex, a region responsible for control processes. A model which integrates this hierarchical organization may better explain how the integration of domain-general and domain-specific elements of the system occurs.

In Defense of Complex Span Tasks as Measures of Working Memory Capacity.

It must be noted that the results presented in this dissertation do not speak to the validity or reliability of complex span tasks as measures of working memory capacity. For example, variance within each span task across each experiment was remarkably consistent (Table 4). This is despite the diverse array of samples ranging from GW students, to Penn State students, to Amazon Turk workers. Further, to ensure a more reliable estimate of working memory capacity, it is considered more methodologically sound to include more than one span score as a measure (Conway et al, 2005; Redick et al, 2012). These precautions are a means of accounting for the different amount of variance explained by each span score in various tasks. However, what this dissertation has shown is that each span score independently, does reflect both domain-specific and domain-general processes and that this insight can facilitate a better understanding of working memory.

Table 4:
Means and standard deviations of span scores cross all experiments.

	Operation Span		Symmetry Span		***r*
	Mean	Std Dev	Mean	Std Dev	
Experiment 1	59	14	30	7	.41
Experiment 2	62	12	29	8	.45
Experiment 3	60	13	28	6	.34
Experiment 4	57	14	28	8	.35

**r* value between OSPAN and SSPAN

Conclusions

The results described in this dissertation provide a strong starting point for the further investigation of the interaction between domain-specific and domain-general processes in working memory. Further research would seek to further understand this relationship in order to come to a more comprehensive account of working memory. In the paradigm presented here, it was found that interference effects did not differ as a function of working memory capacity, whether measured by operation span or symmetry span. However, it could be the case that the measure used was not sensitive enough to elicit large enough difference between individuals with high and low working memory capacities. A logical progression would be to exacerbate the difference in performance between these two groups. This would be done by increasing the proportion of incongruent trials to congruent trials (Kane et al, 2001). This would make the task overall more difficult for the participants, leading to a greater difference in performance between individuals with high and low working memory capacity. Another manipulation would involve changing the arrow stimulus. In experiments where the arrow was used as the target, the no-load condition showed virtually no interference. While the load condition did show measurable interference effects, it would be prudent to make the target less salient, making the task more difficult.

Another approach would look that the interaction between load and target/distractor similarity in further detail. For instance, one could manipulate how much the load matched the target or distractor. For example, it could be assumed that a spatial load of arrows would interfere more with an arrow distractor than a set of squares, as they are more related. This would support the notion that domain-specific effects can be specific not just to object category (verbal vs spatial) but object identity as well. This would go to support the idea of the hierarchical organization of the working memory system. One could go one step further and create custom complex span tasks with matching stimuli as used in the working memory load paradigm. These should better predict performance when the stimuli matched, again providing further evidence for domain-specific effects in complex span paradigms.

Finally, in the paradigm described in this dissertation, there was no manipulation of the amount of working memory load. It would be useful to include a low load condition where resources are not completely consumed. Here there would be extra resources for the processing of the target/distractor. While the controlled attention approach would not predict any differences in performance and a function of span type, it would be interesting to see if domain-specific effects are more likely to occur here.

Taken together, this line of research will provide new insight into the relationship between domain-general and domain-specific information processing in working memory. The data presented here support the idea that the working memory system is hierarchically organized and provides a path forward towards addressing the debate between domain-specific and domain-general processing in working memory.

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