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Executive Control, Working Memory, and Action Planning: An Individual Differences Approach

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Executive Control, Working Memory, and Action Planning: An Individual Differences Approach

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Abstract

Individual differences in working memory capacity and executive control were correlated with choice and performance in the novel voluntary task span paradigm and voluntary memory span paradigms. Measures of encoding were included, all to address the question of how voluntary planning of sequences of behavior is implemented, and to determine what individual difference factors influence bias when selecting complex sequences in the task span. Results indicated that choice is quite different depending on whether sequences will be executed or simply recalled, and both executive control and working memory are expressly involved in these choice processes. Follow up studies manipulating the constructs of executive control and working memory were somewhat unclear, but suggest that loading onto these resources can dampen choice variability and performance. The findings are discussed in terms of past research on voluntary behavior, and recent models of working memory.

Keywords: voluntary task span, task switching, executive control, working memory, individual differences, cognitive effort

Many of our everyday behaviors are organized into sequences of actions. For example, when purchasing items at a grocery store, there are many necessary actions that should be performed in a specific progression. First, one must create a list of what is to be purchased, and remember the items on the list. Then each specific item must be selected, and finally the groceries must be paid for and brought out of the store. While executing this sequence of actions, some tasks might be repeated, such as selecting many of the same type of fruit, while some tasks might require switching, such as selecting a vegetable and then selecting a fruit. Whether one has to switch or repeat tasks, the entire sequence of actions is performed with the ultimate purpose of completing a goal. The customary sequence of actions taken to purchase groceries is organized in a specific manner to allow individuals to successfully achieve their goal in a time-efficient way; how quickly the plan is actually carried out, however, can vary from person to person. This series of actions may be less effortful and quick for some individuals, while for others executing the tasks may require careful concentration and attention to remembering the list.

This real-world example of planned behavior would require executive control for successful completion. Executive control is the set of processes by which the mind exercises command over ongoing programs (Logan, 2003). It allows for choice among a collection of different behaviors and the ability to switch between different tasks, thus supporting the coordination of individual skills and activities in a fluid manner. Switching between multiple behaviors often requires flexible adaptation to changing stimuli in our surroundings. Adjusting our behavior according to changing external demands or internal goals is principal for the construct of controlling cognitive processes, and it can also tap into the idea that we have some sort of volitional control of how we respond to different environments.

Two key aspects of executive functioning are the ability to maintain task relevant information and to switch or update that information as task goals change (Miyake, et al, 2000). These aspects of executive control rely heavily on the role of the working memory system, which is described as the "desktop" of the executive control system. Working memory maintains task relevant information and operations needed to guide current task performance (Logan, 2004; 2007; Oberaur, 2010). Furthermore it allows individuals to keep track of one operation while simultaneously completing another, a skill that is paramount for controlling sequences of behavior. The contents of working memory generally determine our immediate and upcoming thoughts and explicit actions, so controlling the contents of working memory can aid in controlling behavior (Oberauer, 2010). This configuration is necessary for situations such as the coordination of multiple tasks or actions, as some information must be kept active in working memory while other information is integrated and manipulated. Similarly, working memory is also necessary for making decisions or overcoming conflict to determine the appropriate course of action when all relevant options for future performance must be held in mind.

As executive control is evident in many different types of behavior, it must be studied in many different fashions. Two of the most popular experimental methods for studying this construct include the task switching paradigm, and measures of working memory such as span tasks (Logan, 2004). Past research has investigated the interplay of working memory and task switching using a hybrid method developed to reap the benefits of both of these experimental techniques: the task span paradigm (Logan, 2004).

This procedure requires participants to memorize a series of tasks, and then carry out these tasks on subsequently presented stimuli, switching and repeating tasks based on the memorized order. The task span procedure combines working memory and cognitive control, and can provide some insight into whether these processes rely on the same resources. Using this paradigm can also provide insight into whether individual differences in working memory capacity and executive control capabilities influence individuals' performance on complex cognitive tasks, thus explaining some of the variability in participants' volitional behaviors.

The current research focuses on the connection between working memory and executive control, and how these processes relate to the sort of action planning measured by the task span paradigm. Working memory was measured using a customary complex span task, the operation span (Turner & Engle, 1989). This task measures one's ability to recall information (strings of letters) while simultaneously processing another task (basic arithmetic). Executive control is measured with the Attention Networks Test (Fan, McCandliss, Sommer, Raz, & Posner, 2002), which measures executive control via a response conflict paradigm. These two known indices of these constructs of interest will provide individual difference measures with which we can correlate participants' performance on the task span. Examining the correlations among these measures and the task choice and task performance measures from the task span procedure should give us more empirical information about how individuals are able to plan and carry out series of actions, and how these complex behaviors vary depending on differences in cognitive abilities.

Task Switching and Cognitive Control

The task switching paradigm has been used to study cognitive control and flexibility of behavior in response to changing environmental requirements since its inception (Jersild, 1927). Cognitive control is obvious in everyday life, as we demonstrate ability to manage our perceptual, attentional, and memory systems (Logan, 2003). Studying the super ordinate processes that manage these and other basic cognitive systems will inform questions of how our mind is able to "decide" which aspects of our environment to attend or respond to. Further, the answers to these questions can supply insight into topics like intentionality or volitional control of action, which have long been the purview of philosophers (Haggard, 2008).

Researchers have developed many different approaches to studying the mechanisms that allow for adaptive control of behavior in a task switching paradigm. Common to task switching paradigms is a comparison of performance when tasks switch versus when tasks repeat. Each method was developed with the intention of investigating how individuals are able to flexibly control their behavior in a dynamic, often demanding, environment. More specifically, these paradigms aim to determine the nature of the "switch cost" which consistently results in decreased performance when switching between different tasks. Switching between tasks, however this switch is initiated, is effortful, and usually results in increased reaction times and decreased accuracy when completing the switched task. This deficit in performance is a robust and common finding in the task switching literature (Monsell, 2003). This deficit is widely used as an indication of the executive processes that are expected to be taking place when an individual is switching tasks.

To examine this switch cost, researchers may instruct participants to complete blocks of a single type of task, and compare resulting reaction times to those in blocks of mixed tasks (Jersild, 1927; Allport, Styles, & Hiesh, 1994). This approach would allow for the researchers to calculate the overall costs of having to switch many times compared to not switching at all. Researchers might instruct participants to switch tasks in a predictable manner, such as alternation between tasks (Rogers & Monsell, 1995), or cue switches between tasks, either immediately before each task presentation or intermittently throughout an experiment (Meiran, 1996; Sudevan & Taylor, 1987). In this case, researchers would compare reaction times on individual switch trials to repetition trials to measure the costs associated with switching tasks. Finally, researchers may allow participants to switch tasks voluntarily at their own discretion (Arrington & Logan, 2004). This voluntary task switching procedure allows for the analysis of participants' reaction times, but also their choice behavior and switch probability (See Kiesel et al., 2010, and Vandierendonck, Liefooghe, & Verbruggen, 2010 for recent reviews).

Theoretically, researchers expect that if an individual has the intention of carrying out a specific task, he or she will adopt a corresponding task set. This label references the collection of cognitive processes that allow an individual to carry out a specific task according to instructions or requirements. When a participant is instructed to or chooses to switch tasks, he or she must engage the appropriate task set for the new task in order to successfully accomplish it (Rogers & Monsell, 1995). Interpreting the origin of this cost has resulted in two divided schools of thought. Some researchers suggest that the switch cost is reflective of the time it takes the cognitive system to reconfigure itself and prepare for the new task to be completed (e.g. Logan & Gordon, 2001, Rogers & Monsell, 1995).

Preparation for a series of tasks may occur by way of activating a string of appropriate task set parameters from long term memory, recalling these appropriate constraints and rules to working memory for use and manipulation, and directing attention to the task that is explicitly required at that moment. When a task is repeated, there is no need for this effortful reconfiguration process, as the appropriate task set is already engaged. When execution of a new task is required, and therefore activation of a new task set, there is a reconfiguration period encompassing this series of steps, which results in the increased reaction times resulting in the switch cost.

Other researchers propose that the switch cost is really the interference between the execution of the present and previous tasks, which, according to their view, should be present regardless of whether or not the cognitive system performs some sort of reconfiguration (e.g. Allport, Styles, & Hsieh, 1994). This process has been described as "task set inertia", which applies to the idea that the activation of the rules and parameters needed to carry out one task persists in working memory until prior activation is overcome. When the activation of a set of features does not need to be lessened, and when the focus of attention does not need to change to a new task, there is no interference between tasks and therefore no cost. When the current task is a repetition from the last one, we see no decrease in performance from having to overcome the persisting activation of the previously relevant task sets. However when the current task is not a repetition of the previous one, the past task set remains activated and requires inhibition. This process interferes with current task performance, evidenced by the switch cost.

The appearance of the switch cost in the task switching paradigm has prompted much research designed to better understand this phenomenon. Understanding the switch cost should give us more information about cognitive functioning and control, and how the mind is able to execute plans and accomplish goals (c.f. Logan & Bundesen, 2003 for an alternate view). Whether the switch cost is a result of an active cost for trials that require reconfiguration, or no cost for trials with passive perseveration of primed task sets, it is believed to be a valid measure of the time it takes for executive processes to exert some sort of control over behavior, at least those mechanisms that are necessary to switch between multiple behaviors (Monsell, 2003).

Volitional Behavior. As early as the era of psychological pioneer William James, philosophers and researchers alike have recognized the difference between behavior that is under an individual's control, and behavior that is guided or required by environmental factors. This difference stems from the presence of a volitional aspect of behavior. Volition refers to decisions and actions that are under an individual's own control, separable from more automatic processing of environmental input (Norman & Shallice, 1986). The occurrence of an individual exerting agency over his or her thoughts or actions is measurable using experimental methods. One such method that may be used to study volitional behavior, specifically volitional task selection, is one of the most recent applications of the task switching paradigm. The procedure involves voluntary task selection in a multi-task environment. This voluntary task switching paradigm (Arrington & Logan, 2004) allows for internally generated switches between multiple tasks, requiring individuals to decide under their own volition without explicit instructions which task they will perform on any given trial. To permit the volitional choice for which this technique was designed, experimenters often provide bivalent stimuli, on which both tasks may be performed. Generally, participants use separate sets of keys for each task so that the experimenter can code which task the participant chose based on the response. There are other variants of this methodology however, for example participants may respond to a “probe” of some sort at the start of each trial indicating which task will be performed on the following target (Arrington & Logan, 2005). Regardless of the specific methodology, the voluntary task switching paradigm is unique in its ability to capture participants’ volitional choice behavior in multi-task environments.

The standard instructions for the voluntary task switching paradigm request that participants perform each task about equally often and in a random order. These instructions provide a baseline performance frequency to which participants’ actual task choice can be compared. For example, participants instructed to perform the tasks in a random order with no evident pattern should repeat tasks about 50% of the time. In fact, research has shown that participants tend to repeat much more often than that, at a rate of at least 60% in the original voluntary task switching study (Arrington & Logan, 2004). The exact probability of repeating tasks depended on the length of the preparation interval in that research, such that longer intervals resulted in fewer repetitions. Longer preparation intervals also resulted in smaller switch costs. The rate of switching and repeating tasks can provide insight into how demanding on executive processes the act of generating a task switch is and what factors will influence this decision.

From the results of multiple studies that have used this voluntary task switching paradigm, we have learned that external and internal influences on voluntary behavior are both key factors in how participants perform when completing simple tasks. For example, external manipulations such as presenting stimuli in an asynchronous fashion can provoke participants to choose a task associated with the first stimulus that appears on the computer screen (Arrington, 2008). These results provide evidence for the idea that the environment can have a marked influence on behavior. However, this stimulus asynchrony effect is diminished with increased preparation time, which participants may use to form an internal goal. Once such a goal has been established, subjects may actively search for the appropriate environmental stimulus that affords that particular task, regardless of the onset timing. These results demonstrate that internal factors can actually guide our utilization of external information, a cooperative influence of both exogenous and endogenous elements in volitional task selection.

Other internal factors can affect voluntary choice behavior as well. Temporary properties such as the contents of working memory have been shown to bias what tasks participants choose to execute when they are holding information either about stimulus characteristics or location (Weaver & Arrington, 2010). More enduring personal characteristics such as the capacity of attentional systems can also change how individuals respond in volitional task selection situations (Arrington & Yates, 2009). Individual differences in how people control their distribution of attention have been shown to relate to their behavior in a voluntary task switching situation: those with more efficient executive attention networks (as measured by the Attention Networks Test, Fan, et al., 2002) are better able to resolve conflict in situations where there is more than one possible response, and therefore switch tasks more often than those with less efficient networks. The alerting component of one's attentional network, which measures the ability to maintain an attentive state, was positively correlated with participants' switch costs in this voluntary task switching experiment. Whether the outcome of interest in an experiment is task performance or task choice, and whether we measure temporary or more permanent endogenous states, internal characteristics can have a large impact on volitional behavior. These results are instrumental in our understanding of executive control processes as we gain information about the separation of task choice and task performance and also how we might be able to actively manage our cognitive systems with input from our environment and based on internal characteristics.

Working Memory

Developments in working memory research have been both numerous and varied since the idea was first introduced by Baddeley and Hitch (1974). Many different viewpoints about its function and relationship to other cognitive systems have been posed by multiple researchers, and there is still little consensus about the exact specifications of such a system. The label of "memory" may bring to mind one's capacity to retain information for later recall—but to describe this dynamic system with such a simplistic definition would be inadequate. Including mechanisms of attention in the definition of working memory is as important as including a storage aspect. Working memory can be broadly defined as a representational or attentional system that allows for maintenance of some information while simultaneously processing other information. An interaction between memory and attentional processes in this system allows for the dynamic manipulation of information that has been stored while the individual "works" with it. Working memory is commonly linked to a wide-range of complex cognitive tasks. For example, working memory capacity has been previously linked to reading comprehension ability, complex learning (Daneman & Carpenter, 1980), and general intelligence (e.g. Conway, Kane, & Engle, 2003; Fukuda, Vogel, Mayr, Awh, 2010).

A discussion of working memory capacity must define the construct of working memory, and also the construct of capacity. The conceptualization of working memory as relevant to the current research is attention to stored information (Engle, 2002)—where attention is any mechanism that prioritizes some types of information above others, giving one group of representations more influence over cognitive behavior than another (Oberauer, 2010). This definition captures the dynamic interplay of storage and attentional mechanisms. Information that is stored in long-term memory reaches activation owing to the role of attentional processes. It is then available for manipulation and translation. Capacity may have as intensely a debated definition as working memory itself; the proponents of nearly every model have their own definition of the construct. Capacity may refer to the number of concurrent bindings of representations that can occur at one time (Oberauer, Süb, Wilhelm, & Sander, 2007), the limitations of attention (Kane, Conway, Hambrick, & Engle, 2007) or the limited number of available cognitive resources that can carry out processing and storage operations simultaneously (Jarrold & Bayliss, 2007).

Models of Working Memory. The original working memory paper by Baddeley and Hitch (1974) included a central component that was deemed to be responsible for the organization of two rehearsal mechanisms, one responsible for the rehearsal of visual information (visuo-spatial sketchpad), and the other responsible for the rehearsal of auditory information (phonological loop). This three component model has remained the most popular model of working memory for some time. Baddeley and Hitch's model received an update within the recent past with the addition of an episodic buffer (Baddeley, 2000), which was introduced in order to account for the limitations of the originally proposed model. This buffer was proposed to be a storage system, more powerful than the two slave systems, which also had the ability to communicate between long term memory, the central executive, and the two sub-systems. Essentially this buffer is a communication method between all other memory components, with the power to bind information from multiple domains into unitized episodes (Baddeley, et al., 2011).

This organization has been adapted and refined over the years, but the core ideas behind this multi-component system are largely still accepted. More recent models have modified Baddeley and Hitch's (1974) model with the inclusion of an attentional component, which is expected to play a large role in working memory ability. The extent to which attention is thought to impact working memory capacity varies from researcher to researcher, but there are many similarities between models. Most of the current models share the commonality that attention can be included as a non-domain-specific executive control mechanism that allows for relevant information to remain activated (Kane & Engle, 2004; Cowan ,1988; 2005; Lustig, Hasher, and Zacks, 2007). One role of attention can be seen as a mechanism for activating information from long-term memory for the purposes of operating on it.

The collective work of these researchers support the idea that working memory is not really about storage, but is more about the executive control processes that keep goal relevant information active and prevent interference from previously activated concepts by means of inhibition. In fact, these key components of updating relevant information and inhibiting dominant tasks have been described as the building blocks of executive function, lending support for the interdependent relationship between working memory and executive control (Miyake, et al., 2000). These working memory researchers hold the opinion that without a strong executive component, we would constantly be distracted by irrelevant, or no longer relevant, information. This position is explicitly outlined in the model proposed by Lustig, Hasher, and Zacks (2007), who argue that activation in cognitive processes is largely automatic, and controlled inhibition is necessary for the down-regulation of this automatic activation. When this inhibition process is successful, tasks and actions may be carried out without disruption. Executive processes are necessary to eliminate distraction from extraneous information so that working memory content may be manipulated. According to this view, inhibition abilities vary from person to person, accounting for some of the variability in performance on various cognitive tasks, as some individuals will be susceptible to more disruption than others.

Cowan's (1988; 2005) model suggests that there is an independent contribution of the capacity of attention on working memory. The central aspects of Cowan's model involve activated memory, along with the focus of attention within this activation, and central executive processes that are able to manipulate information stored in memory. The focus of attention can hold several items at once in an activated state. These activated items are contained in a general memory store, and are limited only by decay and interference. While the working memory model of Lustig and colleagues (2007) was designed to avoid the construct of capacity, Cowan's idea that capacity is limited by interference would be consistent with their inhibitory control framework, as would Kane and Engle 's (2004) theory of working memory as executive attention.

A working memory model that is particularly relevant to the current discussion of working memory, task switching, and task span comes from research by Oberauer (2009; 2010). The author proposes a dual-system model of working memory including a declarative component and a procedural component. The declarative component of this system is responsible for maintaining information that is available to be manipulated, while the procedural component is responsible for maintaining information that is available to actually carry out the processing necessary for manipulation. An example of the declarative information might be information that could potentially be recalled, such as a list of items, while the procedural information might include the rules and assignments associated with these items, like task sets. According to Oberauer's theory, the declarative and procedural components of working memory are analogous in their structure and execution. A focus of attention in the declarative system may select a stimulus based on some memory component, such as position in a memorized list, and the procedural component will select the appropriate response based on the action plan stored for that task.

The declarative component of this model assumes that in working memory there is an activated portion of long term memory, a region of direct access which stores the bindings of several concepts, and the focus of attention (Oberauer, 2009; 2010). Each component narrows the selected information more than the previous one. This is very similar to Cowan's (1988) model, except that the focus of attention is limited to only one item in Oberauer's proposal. It may be the case that what Cowan suggested was a multi-item activation may actually be the same idea as Oberauer's idea of a region of direct access, which is then further narrowed down in his case (to the focus of attention) beyond Cowan's discussion. The procedural component of Oberauer's working memory is comparable in organization to the declarative component, with an activated portion of procedural long-term memory, a bridge, which holds currently active sets of stimulus-response action plans, and a response focus, which is responsible for selecting immediate actions.

This model is the most recent of all reviewed in the current discussion and Oberauer (2010) readily admits that this model is far from conclusive. However, the ideas proposed by his theory provide an interesting avenue for understanding the mechanisms of working memory and its relationship to task switching. The procedural bridge proposed is able to hold temporary bindings between multiple representations. This is easy to extend to the idea of task sets, which are also temporary representations of linked stimulus, response, and outcome possibilities. Oberauer suggests that the information in the bridge need not be taken from stored long term memory. These bindings can be arbitrary, for example based on experimenter's instructions, and are quite flexible based on our current intentions. Each trial in a task switching experiment relies on this sort of arbitrary stimulus-response binding, which must be activated into the response focus for proper execution. Oberauer additionally mentions that there is generally only one sort of task set activated in the bridge at a time—therefore a task set which is not activated and present in the bridge cannot be responsible for controlling behavior. Alternative response possibilities that may or may not have been recently retrieved from long term memory in the context of an experiment must be brought back into the bridge in order to influence responses, akin to a reconfiguration view of task switching.

Individual Differences in Working Memory. Regardless of the exact organizational details of the working memory system, individual differences in working memory capacity are believed to be related to a person's ability to control his or her attentional resources (Engle, 2002; Kane, Bleckley, Conway, & Engle, 2001). Control of attention is a concept believed to be measured with task switching experiments. There are three main areas where working memory capacity can affect an individual's ability to switch between multiple behaviors, especially a planned series of behaviors. Working memory capacity can affect an individual's ability to input information into the working memory system to be stored. This process is modulated by attention (Vogel, Woodman, & Luck, 2005). It can also affect the ability to keep the stored information properly organized or limit the efficiency of updating and manipulating stores—in order for the working memory system to properly function, individuals must pay attention to the processing task, or whatever they are doing to manipulate information, while maintaining the integrity of their stored list (Redick, Calvo, Gay & Engle, 2011; Zhang, Verhaegen, & Cerella, 2012). Finally, working memory capacity can affect an individual's ability to retrieve information from a stored state in order to actually carry out desired tasks—attention is required at least for the recall component of working memory capacity tests (Asian, & Bauml, 2011; Healey & Miyake, 2009). Variability in the capacity to properly carry out one stage of this process can affect the ability to execute a series of tasks, potentially resulting in decreased performance. Examining the differences among individuals' performance can help to examine and explain the interaction between attention and working memory, and how these processes work together to support control of action.

Past research has failed to demonstrate a conclusive link between working memory capacity and cognitive control as measured by switch costs (Kane., et al., 2007; Miyake, et al., 2000; Oberauer, Süb, Schulze, Wilhelm, & Wittman, 2000; Oberauer, Süb, Wilhelm, & Wittman, 2003). Collectively these researchers suggest that perhaps the switch cost is not a viable measure of cognitive control at all, which does not go as far as to say that working memory capacity is unrelated to cognitive control itself, just that it is not related to the measurement of switch costs used in many cases.

Another such examination with contrasting results can be seen in work by Butler, Arrington, and Weywadt (2011), which extended past research on this link between cognitive control and working memory to volitional environments. The authors correlated participants' working memory capacity scores to their likelihood of switching tasks, and the costs they incurred when doing so in a volitional multi-tasking environment. Results suggested that participants' working memory capacities were linked to the costs associated with switching, such that those with higher working memory capacities were most likely to have small switch costs especially when the preparation interval was quite short. However, working memory capacity was not associated with the probability of switching tasks. Significant effects on task performance, although not task choice, were explained by the authors in the context of the above conflicting results in terms of the relationship between working memory capacity and the ability to retrieve and represent information from long term memory for use in current activity. Participants who have greater working memory capacities are more efficient when retrieving the response rules for a switched-to task, and therefore have smaller switch costs. The lack of a connection between working memory capacity and task choice leads to the suggestion that the choice process and the processes necessary for maintaining task preparation are separate. Overall conclusions of this research suggest that those with high or low working memory capacities are equally able and likely to move between different tasks however those with lower working memory capacities are less efficient when doing so.

Measurement techniques. From a methodological standpoint, differences in working memory ability can be measured in an almost limitless number of ways. In general, performance on various working memory tasks is believed to measure this systems' capacity, regarding storage and processing (Conway, Kane, Bunting, Hambrick, Wilhelm, & Engle, 2005). Most of the measures used to test this capacity involve some sort of storage component, such as remembering a string of digits or letters, and some sort of processing component, which may be interleaved with the presentation of items to be stored. The processing component is likely something that requires the shift of attention away from the storage component. One of the most popular working memory capacity tasks is the operation span (OSPAN), developed by Turner and Engle (1989). Subjects are required to make responses to strings of math operations, judging whether the presented operation is true or false. After each operation, they are presented with a simple word. After a varying number of operation strings and words are presented, the participant is instructed to recall as many words as possible. The number of words they correctly remember is the critical score. An automated version of this task used in the current research includes similar tasks and has similar reliability and construct validity (Unsworth, Heitz, Schrock, & Engle, 2005).

There are other related working memory capacity tasks used in the field as well. For example, instead of judging the accuracy of math operations as in the OSPAN, participants may be asked to judge the reasonableness of a simple sentence. This judgment would then be followed by a to-be-remembered word, as in the previously described OSPAN task. Participants can also be asked to maintain multiple counts of presented stimuli, constantly updating the tallies of various presentations requiring updating and maintenance of multiple memory traces. What is common among most of these measures is that they engage attention while also engaging memory processes. In fact, research by Lepine, Bernardin, and Barouillet (2005) suggests that all that is needed to disrupt working memory capacity is a task that requires some amount of attention. Based on the results of the aforementioned span tasks, it appears that the tests are actually measuring some aspect of cognition that is quite fundamental.

Task Span

As has been discussed above, the cognitive processes of attention and memory are highly intertwined and the coordination of these processes is necessary for successful multitask behavior. Studying these two constructs using a hybrid experimental method is valuable because it allows us to gain information specifically about their interaction. This knowledge can provide insight about cognitive control mechanisms and how individuals are able to flexibly switch between multiple behaviors while maintaining relevant information in working memory. The hybrid experimental method used in the current research, referred to as the task span paradigm, was developed by Logan (2004).

The paradigm involves the memorization of a series of task cues, and performance of these tasks on subsequently presented stimuli. The procedure includes a study phase, during which participants are presented with a series of task name cues. They are instructed to encode the presented order of these cues for later use. The second phase of the procedure is the test phase. During this part of the experiment, participants are presented with a series of bivalent stimuli and must recall the memorized order of task cues to coordinate the task they are completing with the corresponding cue they had previously memorized. Throughout the implementation of the task span procedure, participants must repeat and switch tasks as they were previously instructed. During the test phase, participants' reaction time to the targets is measured, as well as their accuracy in remembering the corresponding cues from the study phase. Logan (2006) compared participants' accuracy and reaction time results in the task span paradigm to the same measures on a standard memory span, and to blocks of single task trials. Results from the memory span task indicated that switching between task names did not result in large increases in reaction times as did switching between tasks when performance was necessary in the task span procedure. This suggests that switching in the memory span procedure was not effortful, and retrieval of tasks differs in that procedure when compared to the task span. Most of the increased reaction time needed to switch tasks in the task span paradigm likely does come from some sort of reconfiguration process of the cognitive system.

The span of tasks participants are able to execute has been shown to be comparable to standard memory span measures, which suggests that there is no trade-off between memory for the span and the processing capabilities necessary to actually execute the tasks (Logan, 2004). Whether participants need to remember a series of items with the intention of simply recalling them, or with the intention of actually performing associated tasks, their span is the same (although the time required to execute the spans does differ). This finding suggests that the structures necessary to plan for the task's performance do not interfere with the structures necessary to store the list of items. This result is consistent with a multi-process model of working memory, such that multiple operations may be occurring at one time without, or with limited, consequences on performance. Specifically, this lack of a trade-off between storage and processing is consistent with Oberauer's (2010) view of dual declarative and procedural memory systems. Such a multi-store system would account for the results that simple memory span and more complex processing elements do not rely on the same memory resource. Although the two components may work in analogous ways, use of one type of memory resource does not limit the use of the other.

The previous task span work conducted by Logan (2004; 2006; 2007) did not manipulate or measure any variables related to the cue encoding process. This deficit has encouraged development of several studies that have intended to bridge this gap. For example, Mayr (2010) implemented a study designed to determine the role of cue and task switches in the task span procedure. Using a 2:1 cue to task mapping, the experiment demonstrated that there were substantial costs associated with switching between cues, even when tasks did not switch, and vice versa. These data support the idea that action plans may rely somewhat on superficial auditory codes that represent tasks to be completed in a series. These results were analogous to previous 2:1 cue to response mappings used in the cued task switching paradigm, which found similar evidence that cue switches account for a large part of the switch cost. Mayr (2010) concluded that overall, internally memorized cues elicit behavior that is much like that elicited by externally presented cues. This finding, coupled with the deficit of knowledge about encoding in the task span paradigm, prompted several research questions that were addressed in a study by Reiman, Arrington and Weaver (in preparation) described below.

Past research has indicated that we have some idea of how individuals perform when carrying out sequences of actions, (Logan, 2004; 2006; 2007, Schneider & Logan, 2005), but we do not know whether their encoding behaviors change when they are required to perform a series of tasks or simply recall items from memory. We know that individuals are able to memorize a series of actions, and then perform tasks at a later time, but we do not know how this process may change when individuals are in control of the sequences they create. How might the retrieval of a series of planned actions vary when encoding process take place with exogenous instruction, or endogenous production? By extending the task span paradigm to voluntary environments, and also investigating the nature of encoding behaviors used in the procedure, we addressed these questions.

Logan's (2004; 2006; 2007) task span work provided a basis for the experiments, with some additional areas of interest. Participants were asked to memorize a sequence of tasks, and then perform these tasks on subsequently presented stimuli, as in the original experiments. However, they were also asked to press a key after the presentation of each task cue, in order to secure a measure of encoding time. We measured encoding and performance reaction times and accuracy, and analyzed these measures as a function of the overall complexity of the presented lists as well as local task transitions (i.e. repetitions and switches). The second experiment was quite similar, with the difference that participants were not encoding a list given to them by the experimenter, but instead they were generating their own sequence of tasks for later performance. The same generation and performance reaction times and performance accuracy were measured, and analyzed as a function of the list complexity and transition.

Results of the two experiments suggested that whether encoding externally-defined lists, or internally generating sequences of tasks, participants tend to perform in a comparable fashion. In general, memory and reaction time measures suggest that lists with more switches and greater complexity tend to be the most difficult for participants to execute. Presumably as a consequence, these lists tended to be chosen the least often when the parameters of the experiment required volitional behavior. We also found that by using the reaction time and memory data from the first experiment, we were able to accurately predict what choices a separate group of participants would make in the second experiment. The predictive ability of participants' performance measures seem to suggest that they are actually sensitive to the increased cognitive effort that more complex lists will require, and they therefore avoid those types of sequences.

Current Study

Chronbach (1957) called for a unification of what he described as the "two disciplines of scientific psychology". He was referring to the tendency of psychological research to branch into experimental and individual difference fields, with few studies marrying these two approaches. Combining these approaches to psychological study, in his view, would allow for a comprehensive examination of human behavior. The current research is designed with this approach in mind, combining experimental and differential approaches to address the question of how different components of cognitive behavior interact in a multitask environment.

The current study includes recognized measures of working memory capacity and attentional control: the Operation Span task (Turner & Engle, 1989) and the Attention Networks Test (Fan, et al, 2002). Diversity in individuals' abilities in these areas provides us with rich individual differences data with which we can correlate performance and choice measure in the task span paradigm, and allow for a sort of fine grained manipulation of these two constructs (Vogel & Awh, 2008). This correlation allows us to investigate what factors contribute to participants' sequential choice when they are voluntarily selecting actions to develop a plan for later execution, such as in the voluntary task span paradigm.

OSPAN. The current study utilizes a working memory span task to measure participants' working memory capacity. Previous work has used the operation span task (Turner & Engle, 1989), but the original version of the task requires a large role of the experimenter. In light of this characteristic, an automated version of the task was chosen instead. The automated version of the task is completely mouse-driven, is paced according to each subject's average response times, requires no experimenter interaction, and is automatically scored, (Unsworth, et al. 2005).

In the automated OSPAN, participants are asked to solve a series of simple math operations which are interleaved with the presentation of single letters. After a designated number of operation-letter pairs has elapsed (3-7 pairs), the participants are presented with a matrix of letters, which they use to indicate which letters they saw in the appropriate order. The task measures participants' ability to simultaneously process and store information, characteristics of the working memory system.

ANT. Executive control is measured with the Attention Network Test (ANT) (Fan, McCandliss, Sommer, Raz, & Posner, 2002). As described above, this measure includes three areas of investigation: gauging the skills of alerting, orienting, and executive control. The measure was designed to separate these three networks in accordance with the three components of attention described by Posner and colleagues (Posner & Peterson, 1990; Posner & Rothbart, 2007). The alerting network maintains a ready state, allowing individuals to receive information from the external environment.

The orienting network allows individuals to select which sensory input will receive attention, and finally the executive control network monitors for and resolves conflict in response selection. These three networks are only very weakly correlated to one another, a statistic which suggests independent utility of the systems (Fan et al., 2002).

The ANT measure involves two paradigms commonly used in attention research: a cuing task and a flanker task. Scores for the alerting, executive control and orienting networks are calculated by comparing different sorts of cueing and target situations. For example, in the alerting network, scores for trials when participants are alerted to the oncoming target are compared to scores for trials when no such warning occurs. A full description of all cueing and target possibilities is presented in the Methods section and depicted in figure 1.

Voluntary Task Span. The voluntary task span procedure is very similar to the task span procedure described above, with the exception that instead of encoding sequences of tasks, participants are asked to generate sequences of six tasks themselves. They then perform these tasks in the same order as they generated them on subsequently presented stimuli. This extension of the task span procedure (Logan, 2004; 2006; 2007) will allow for an examination of the integration of working memory and executive control processes, with the inclusion of a volitional task selection aspect. This procedure is depicted in figure 2. Sequence choice is operationalized in terms of the deviation from perfectly random and equivalent list selection. Smaller deviations from perfectly even task choice will likely be a result of the tendency of these participants to choose more complex lists that include more switches.

Voluntary Memory Span. Reiman, et al.'s results (in preparation) are not conclusive as to whether participants' sensitivity to the increased effort required to execute the more complex sequences and the likely resulting preference for less complex sequences stems from the higher demand on working memory processes for these lists or the executive control resources needed to switch between multiple tasks. This question led to the inclusion of a voluntary memory span task in the current study. This task requires participants to generate a sequence of six tasks, and then recall this sequence, without having to actually perform the tasks associated with the cue names.

Predictions. Measures of participants' executive control capabilities (from the ANT) and working memory (from the OSPAN) were correlated with their choice and performance in the voluntary task span and voluntary memory span procedures. Past research with voluntary task switching and the ANT measure of executive control has shown that task choice, but not task performance, was correlated executive control capabilities (Arrington & Yates, 2009). More efficient executive control networks were associated with greater likelihood of switching. Based on these results, we expect in the current study that executive control capacity will be associated with greater variety of sequence choice in the voluntary task span paradigm. Executive control as measured by the ANT is not expected to be related to the switch cost, based on the past research of Arrington and Yates (2009). This measure of executive control is imperfect, and likely reflects only the portion of executive control related to overcoming response conflict—this would not be related to switch costs as it was not in the past research.

Based on the work of Butler, et al. (2011), working memory capacity is not expected to correlate with task choice. It is, however, expected to correlate with performance in terms of the switch cost. The definition of working memory applied to the current research is attention to stored information. This construct is certainly likely to be related to the switch cost, as participants must refresh the task sets associated with the past task when switching, which will be more efficient for those who are able to better able to shift and update their attention to the stored rules.

As mentioned, above, it is unclear whether the biased sequence choice results of Reiman, et al. (in prep.) are a result of increased demands on working memory or cognitive control. The results of the voluntary memory span portion of the study should tell us where the cognitive demand of more complex sequences comes from. In this previous work with the task span paradigm, we suggested that participants were less likely to choose to complete more complex sequences because they were sensitive to the increased cognitive effort these lists would require. If we see in the current study that participants are unlikely to choose complex sequences in the voluntary task span procedure, but they are choosing these sequences in the voluntary memory span element of the study, we will conclude that our previous results cannot be explained by demands on working memory. Instead, this would indicate that participants are more sensitive to the executive control resources that are needed to complete such sequences, and choose which sequences to complete based on a desire to limit cognitive control effort. If we see that participants do not choose complex sequences in either the voluntary memory span or the voluntary task span procedures, we might conclude that complex sequences require more working memory resources, and participants attempt to avoid the effort required to remember the task names as well as the effort of actually switching tasks at performance.

Experiment 1

Method

Participants. Participants included 89 Lehigh University undergraduates who participated in two one-hour sessions for partial course credit. All participants reported normal or corrected to normal vision and signed a document indicating their informed consent to participate in the experiment.

Stimuli and Procedure. Stimulus presentation and response recording was controlled by E-Prime software (version 1.1) running on Dell Dimension computers with 17 inch CRT monitors. Viewing distance was not controlled. The experiment involved administration of four components: the ANT, the OSPAN, the voluntary memory span, and the voluntary task span procedures. These four tasks were partially counterbalanced across participants: each individual completed either the memory span or task span at the start of a one-hour session, followed by either the ANT or the OSPAN. In the second session they completed whichever tasks they had not yet done.

OSPAN. The operation span procedure (Engle & Turner, 1989) was administered as per the customary directions associated with this task. The current study used an automated version of the task, which was mouse-driven, computer-paced and scored automatically (Unsworth, Heitz, Schrock, & Engle, 2005). This task was downloaded from a website made available by the researchers (http://psychology.gatech.edu/renglelab/Eprime1.html).

In the automated operation span, participants were first given extensive practice in three aspects of the task: the letter memory task, the math operations task, and the combination of these two aspects. During the letter memory practice, a series of letters appeared on the screen one at a time and then participants were asked to recall the letters in the same order in which they were presented. In both the practice and the actual administration, letters remained onscreen for 800 msec. At recall, the participants saw a 4 X 3 matrix of letters (F, H, J, K, L, N, P, Q, R, S, T, and Y) from which they selected their responses. The math operations were practiced to determine participant's average responses times to the arithmetic problems. First the computer screen showed a simple math operation. Once the participants solved it they clicked the mouse to advance to a screen that presented a potential answer. Participants then clicked a button labeled either "true" or "false". Participant's response times were recorded, and their average time to respond was used to calculate a time limit for the later, full version of the task. This limit was calculated as their average response time, plus two and a half standard deviations.

The final element to the practice phase included all aspects of the task. Participants were shown a math operation, which they clicked to advance. They then determined if the presented number was a true or a false response. Finally they were presented with a letter to remember. Three to seven pairs of operations and letters were presented, after which the letter matrix was presented for them to recall the letters in order. Feedback was presented after the recall, indicating how many letters they answered correctly, and how many math operations they got correct. The data collection phase of the span task proceeded exactly as the final practice phase. There were three blocks, consisting of administration of each of the set sizes three times, resulting in 75 total math operations and letters. Participants had to maintain 85% accuracy on the math operations for their data to be viable, which was emphasized to them during instruction. This limit was imposed to ensure that they were not rehearsing the letter series when they should be devoting their cognitive resources to processing the math operations. The researcher is provided with five scores: OSPAN score (sum of perfectly recalled sets of letters), total correct (total number of letters recalled in the correct position), math errors (total number of the following two errors), speed errors (taking longer than the allotted time to complete the math operations), and accuracy errors (computation errors on math questions).The experimenter stayed in the subject running room during all practice phases to ensure that the participant learned the task satisfactorily.

ANT. The Attention Networks Test (Fan, et al., 2002) was also administered as per the customary directions associated with this task. This task was downloaded from a website made available by the researchers (website address unavailable).

The ANT required participants to determine whether a central arrow pointed to the left or right. The arrow always appeared either above or below a fixation cross and was sometimes accompanied by flanker arrows. Congruent flanker trials consisted of targets made up of five arrows all pointing in the same direction. Incongruent flanker trials consisted of targets made up of a central arrow pointing one direction, while two flanker arrows on either side pointed in the opposite direction. Neutral trials were made up of only the central arrow flanked by two dashed lines with no arrowheads on either side. A sample trial and sample cues and targets are presented in Figure 2. The alerting network is assessed by comparing reaction times on trials with no cue, and trials with double-cues. The orienting network is assessed by comparing the reaction times of the central-cue and the spatial-cue conditions. The executive network is assessed by comparing the reaction times from the compatible and incompatible flanker trials.

The trial timeline was made up of the following events: first, participants saw a fixation cross for a variable time span, between 400 and 1600msec. This was followed by a warning cue, for 100msec, and then a second fixation period, for 400msec. In the single-cue condition the cue indicated where the target would appear, either above or below fixation. In the double-cue or central-cue conditions, there was no spatial information presented; the cue simply indicated that the target would appear soon, but did not indicate where. Following the presentation of the warning cue, the target was then presented until the participant responded, for up to 1700msec. Finally, a post-target fixation period lasted for as long as was necessary for the entire trial's duration to reach 4000msec. The session included 24 practice trials and 3 blocks of 96 trials each.

Task Span. For the task span portion of the study, participants categorized objects according to two dimensions: height and shape. Stimuli included black outlined rectangles and ovals on a grey background. Tall shapes were 2 cm by 5 cm, short shapes were 2 cm by 3 cm. Tall and short rectangles and ovals appeared in a random order about equally often.

The events of the generation and test phases of the volitional task span procedure are detailed in Figure 1. Each block began with a screen with the words "GENERATION press the space bar to begin". This was presented until the participant responded—*c* and *m* keys were pressed using the index fingers of each hand in response to generation prompts. Subsequently a series of 6 question marks were presented, each until the participant indicated whether they chose the height or shape task. This keystroke was used to measure generation response time. Each prompt remained on the screen until the participant's response was recorded, and there was a 500 msec blank interval before the next presentation. Participants were instructed to memorize the order of the tasks they generated for use during the test phase, and the importance of responding quickly to the prompts and maintaining the sequence in memory was stressed by the experimenter.

Following the generation phase, participants viewed a warning screen, displaying the word "TEST" for 1000 msec. Participants then saw a sequence of six stimuli presented one at a time. Upon this presentation, they were asked to make height or shape judgments according to the previously generated and memorized sequence (height judgments were categorized as tall or short, shape judgments were categorized as rectangle or oval). The stimuli were presented until the participant responded with their shape or height judgment, with a 100-msec RSI. The *s, d, k,* and *l* keys were pressed using the middle and ring fingers on each hand in response to target presentation. During the instruction of the procedure, the experimenter stressed the importance of responding quickly and accurately to the targets. Target response time, target accuracy, and memory for the correct task were recorded.

Participants completed 16 trials of practice with both the height and shape tasks and 4 complete blocks of practice with the full procedure. For actual data collection, the participants completed 60 generate/test blocks. During the practice phase of the experiment, participants were familiarized with 20 possible sequence orders, presented in Table 1, which include all possible sequence orders of two tasks three times each. They were instructed to attempt to generate all of these sequences in a random and equal fashion.

A key feature of these sequences, which related to the independent variables in this experiment, was the overall global structure of the lists. There were two measures of this global structure: the switch value and the complexity score. The switch value was based on the overall number of switches in the list (5 levels based on a maximum of 5 switches in a 6-task list). The switch value of a list is a very intuitive way of thinking about the difficulty participants may have when encoding and performing a task span sequence. The switch cost described above lends some support for the idea that lists with more switches would be more difficult for participants. Switching back and forth between different tasks clearly results in longer response times and decreased accuracy in most task switching studies, suggesting that the act of switching results in a more challenging or complex process.

The complexity score measure provides a different way of investigating this concept that may account for the ease associated with more heavily-structured sequences. A complexity score was adapted from work by Herb Simon (1972). Each sequence was assigned a score based on the way in which it could be "simplified". For example, a sequence such as "height, shape, height, shape, height, shape", could be simplified to "3(HS)", and would be assigned a score of 5 according to this measure. There were four possible scores for these 20 sequences: 5 (which is the same as 5 switches), 8 (which is the same as 1 switch), 11, and 14. Using both of these measures for the complexity of sequences is beneficial because they complement each other in some respects, but also provide some different information about the structure of lists, and how participants are able to use this information when encoding sequences and making judgments according to these list orders. The complexity score analyses are presented in appendices A-C, as the pattern of results was very similar for the switch value and the complexity score.

Voluntary Memory Span. The voluntary memory span was very similar to the task span procedure. Participants responded to a series of six question marks in the generation phase by indicating either the shape or height tasks using the *m* or *c* keys, just as described above. There was however, one major alteration from the task span during the test phase. When presented with the series of six shapes in the test phase, there was no task performance. Instead, participants simply were tasked with remembering the sequence that they had previously generated. They recalled the sequence by pressing the same keys that they had used in the generation phase. They did not actually perform the judgments on the presented shapes. The memory span task was the same length as the task span administration.

Results

Analyses in Experiment 1 were based on data from 81 participants. Significance testing was performed at $\alpha = .05$. Results related to the main hypotheses are presented here. Additional analyses can be found in Appendix A.

OSPAN. Participants were eliminated from analyses if their math accuracy dropped below 85%, which indicated that they likely were spending the processing period rehearsing the letter sequences, counter to the instructions. This exclusion criterion applied to 5 participants.

The OSPAN produced two dependent measures—the absolute score and the total correct score. The absolute score was the sum of the number of correctly positioned items in each perfectly recalled list. The total correct score was the total number of recalled items, regardless of whether the entire list was recalled correctly. The latter was a more lenient measure of memory span. These two measures were extremely highly correlated *r*

= 0.934, $p < 0.001$. We therefore limited our analysis to the more stringent measure (absolute score). The mean absolute score was 47.63 (possible range = 0-75) and the standard deviation was 17.12.

ANT. Response times on trials with no warning cue and trials with a double warning cue were compared as an index of the alerting score ($M = 47.26$, $SD = 23.42$). Response times on central cue trials and spatial cue trials were compared as an index of the orienting construct ($M = 34.96$, $SD = 22.61$). Finally, response times for targets with congruent flankers were compared to targets with incongruent flankers as an index of executive control ($M = 112.86$, $SD = 40.29$).

There was a significant correlation between the alerting and orienting networks $r = -0.313$, $p = 0.005$. These two networks were not, however, correlated with the executive control score (Alerting: $r = 0.115$, $p = .312$, Orienting: $r = -0.004$, $p = .971$).

Voluntary task and memory spans. Data were trimmed to eliminate trials on which participants made errors in responding to the target, as well as the trials following these errors as they were significantly slowed. Trials for which response times were lower than 150 ms or greater than 4000 ms were also eliminated from analysis. Elimination occurred only for the specific trial where the error or response time violation occurred, not for the entire list. Target accuracy was very high, 92%. Three participants had target accuracy at chance in the task span, and were excluded from analyses.

Choice. As depicted in figures 3a and 3b, participants' choice patterns both in the memory span and in the task span were heavily biased towards less complex sequences, although more so in the task span condition. Two related summary measures of choice patterns were calculated to produce simple scores that captured participants' choice behaviors in the task and memory spans. The first involved the average deviation of participants' choice from the ideal equivalent choice pattern. There were 20 possible sequences based on the mandatory characteristics of three instances of the height task and three instances of the shape task. Each of the sequences had a perfect complement that had the same structure although with the tasks reversed. If participants followed the instructions to complete all of the sequences equally often, they should have executed each of the pairs with a proportion of .10. We therefore calculated an average deviation score accounting for the proportion of blocks participants chose a specific sequence and how this differed from the ideal .10 proportion. The second measure captured the relation of this deviation to the number of switches within a list, or switch value, based on the slope of the best-fit line encompassing the choice deviation for each list type, excluding the 5-switch condition. For more than 75% of participants this deviation score was negative, indicating that they were less likely to select sequences with more switches. The other participants were very near to 0, with a maximum slope of .012.There was a significant difference in choice as a function of complexity between the task span and the memory span, $t(163) = -2.968$, $p = .003$.Participants showed a greater avoidance of more complex lists in the task span than in the memory span.

Performance. Data were analyzed separately for each dependent variable: prompt response time, target response time, and memory. Results for the prompt response time analyses are presented in Appendix A. Memory was calculated on a task by task basis, and also for entire lists. These two measures were very highly correlated $r = 0.950$, $p < 0.001$, therefore only the more stringent measure of memory, the list memory, is reported. Task memory analyses for the within-group differences can be found in Appendix A. The dependent measures of task memory, prompt response time and target response time were first analyzed as a function of the local measures of serial position and transition between trials (either a switch or a repetition). Subsequently each dependent measure, including list memory, was also analyzed as a function of more global characteristics of the sequences, specifically the overall number of switches in the list and the complexity score that was based on the patterns and structure of the list. These global analyses were conducted collapsing across all serial positions and both transition types. Results for the serial position and complexity score analyses can be found in Appendix A.

Within-Group Differences.

Target Response Times. Results of repeated measures ANOVAs suggest that local measures of task transition (switches and repetitions) had significant impacts on target response times for both the memory span and the task span Switching tasks resulted in overall slowed response times to the target. Switching back and forth between simple recall responses does require more time than repeating responses in the memory span, although this difference was not as large as that between switching tasks and repeating tasks in the task span (repetitions: $M = 773$, $SD = 508$, switches: $M = 1244$, $SD = 597$). This was indicated by a significant interaction in a 2 x 2 RM ANOVA with condition and transition as factors, $F(1,98) = 555.82$, $p < .001$. The switch cost at task performance was quite large for the task span, $F(1,82)$ 512.77, $p < .001$, and while it was also significant for the memory span, $F(1,81) = 6.84$, $p = .011$, it was not quite as large of an effect.

More complex sequences elicited longer response times than those that had fewer switches and/or a more defined structure whether participants were simply recalling the task names or actually carrying out the tasks. There was also a significant interaction between condition and switch value, $F(4,324) = 91.57$, $p < .001$. This is depicted in figure 4. Switch value, $F(4,308) = 15.74$, $p < .001$, had significant effects on participants' response times to the targets in the memory span. The same pattern held for the task span, with switch value, $F(4,288) = 84.49$, $p < .001$ significantly impacting target response times.

List Memory. List memory was analyzed only as a function of the global measures of complexity score and switch value using repeated measures ANOVAs to investigate differences across each of these variables separately. Both of these variables had significant effects on list memory for the memory span and the task span so, as above, only the results of the switch value analysis is presented here. A 2 x 5 repeated measures ANOVA exploring the effects of condition and switch value on list memory indicated that there was a significant interaction of these two variables, $F(4,320) = 3.644$, $p = .006$. There was a sharper decrease in list memory for lists with higher switch values in the task span compared to the memory span, when excluding lists with five switches, illustrated in figure 5. Participants were less able to remember the entire list for more complex sequences than they were for the more simple sequences. The switch value, $F(4,308) = 14.53$, $p < .001$, had significant main effects on participants overall memory for sequences in the memory span. The switch value, $F(4,288) = 26.14$, p < .001, had a similar effect of decreasing memory for more complex lists in the task span.

Individual Differences. Unsurprisingly, participant's choice in the memory span was significantly correlated with their choice in the task span, $r = 0.524$, $p < 0.001$. Those who deviated from the expected choice pattern tended to do so in both conditions.

Measures from the Attention Networks Test were correlated with measures of choice and performance in both the task span and memory span, described below. These analyses are followed by correlations between working memory capacity and these choice and performance measures. A full summary of all correlations between performance and choice measures and OSPAN and executive control scores can be seen in Table 2.

Orienting scores from the ANT were moderately correlated with participants' memory for lists in the task span, $r = - 0.212$, $p = 0.061$. Otherwise this measure and the alerting score did not significantly relate to any of the variables of interest in this study, and are eliminated from further discussion. Executive control was significantly related to choice in the memory span and in the task span. As the executive control score increased, which indicates a poorer ability to resolve conflict, the likelihood of deviating from the ideal choice pattern increased.

Executive control was also significantly related to participants' memory for the overall lists, but only in the memory span condition. As participants' executive control scores improved (indicated by lower values), their memory for lists in the memory span increased. This relationship was further explained as the effect of the switch value of the lists was examined. A summary measure was calculated based on the slope of a best fit line connecting the list memory scores of sequences with one, two, three, or four switches. The five-switch condition was excluded from the measure because of the increased memory for this highly structured sequence (e.g. HSHSHS). This summary measure of list memory as a function of switch value in the memory span was also significantly correlated with executive control scores. Participants with poorer executive control networks had lower scores on this calculated measure, indicating that there was less of an effect of list complexity on memory for these individuals. This interesting finding could be a result of those with lower executive control scores showing lower memory overall, therefore there was less of a decline in memory as a function of switch value for these individuals. That interpretation is consistent with the significant negative correlation between executive control and list memory discussed above.

List memory in the task span condition was not significantly correlated with the measure of executive control from the ANT. Approaching this memory score as a function of the switch value of the lists did not indicate any additional relationship.

Response times to prompts, or the time required to generate sequences, and response times to targets were unrelated to the executive control score in the memory span and in the task span. Executive control scores were related to switch costs, however, although only in the task span.

Working memory capacity as measured by the OSPAN was significantly correlated with participants' choice behaviors in the task span. As their working memory capacity increased, this choice summary measure decreased, suggesting less deviation from the ideal equivalent choice pattern. There was no significant relationship between working memory capacity and choice in the memory span, however.

Working memory capacity was marginally related to overall list memory in the task span and the memory span. As working memory capacity increased, the memory for lists increased as well. Analyses of list memory as a function of the switch value of the sequences were conducted to determine if there was a relationship with working memory capacity, as previously mentioned with the executive control score above. This list memory complexity measure was marginally correlated to working memory capacity in the task span but not at all correlated in the memory span.

Finally, measures of response time performance were also compared with the working memory capacity absolute score. Response times to targets were not significantly correlated with this measure in the memory span or in the task span. Working memory capacity was marginally related to switch costs in the memory span. The negative correlation suggests that as working memory capacity increased, the difference between repetition and switch trials in the memory span decreased. Response times to prompts were unrelated to working memory capacity in the memory span and in the task span.

Discussion.

This experiment explored participants' sequence choice and performance behavior in voluntary task and memory span procedures. The effects of serial position, transition, sequence complexity and switch value on generation and target response times and list memory in the task span were completely consistent with the results of Reiman, et al. (in prep). In Experiment 1 participants' response times and memory for sequences was negatively impacted by greater complexity and switching tasks, both on a local task by task basis and a more global overall level. The addition of measures of encoding in past research indicated that the same variables that had a negative effect on sequence performance also made sequence encoding and generation more difficult. This was replicated in the current study, as participants also showed negative effects of complexity and switching between tasks when they were generating sequences, although these effects were much smaller. From these similar results, we can presume that there is a possible parallel between the processes occurring during the generation of sequences and the recall and performance of them. We can speculate that the same sort of endogenous control processes are necessary in both stages of the task span paradigm, but there are aspects of behavior unique to performance that are more negatively impacted by sequence complexity.

Choice behaviors in the past experiments led us to the conclusions that participants are sensitive to the demands of more challenging sequences, and therefore presumably choose to execute them less often. One of the open questions from Reiman, et al. (in prep) was why subjects showed a bias in sequence choice toward less complex sequences. The current experiment used a combination of approaches to address this question. First the experiment included the voluntary memory span procedure, which required some aspects of cognitive processes needed in the task span (encoding and retrieval of a sequence) but did not require performance of the tasks. Additionally the experiment included an investigation of the individual difference measures of executive control ability and working memory capacity and their relationship with participants' sequence choice and performance, both in the task span and in the memory span. We expected that if the previously seen choice bias was a result of the greater working memory demands of these more complex sequences, then participants' working memory capacity as measured by the OSPAN scores should be related to their choices. If this preference was a result of sensitivity to the increased executive control resources necessary for the more complex lists, then their executive control scores should be related to their sequence choice. Further, a difference between the task span and the memory span in regards to these correlations would tell us that there is a difference in the circumstances under which participants choose or do not choose the more complex sequences depending on the unique demands of each sort of span task. Differences in the way the general variables included in this experiment impact the memory span and task span would indicate that participants engage in different sorts of behavior to execute each of these span tasks.

Analyses directly comparing the memory span and task span (refer to Appendix A) indicated that there were significant differences in the way participants generated and performed sequences when they had to simply recall task names compared to actually carrying out task switches in a memorized order. In general, manipulations of complexity and switching tasks affected participants' response times and list memory in the same manner, but to a lesser extent, as for performance in the task span. Choice was also found to be quite difference across conditions, with significantly less bias in choice in the memory span condition than in the task span condition. This finding supports the idea that there is something special about needing to carry out the tasks in the task span procedure that pushes the bias in sequence choice toward more simple sequences. Recent research (Kool, McGuire, Rose, & Botvinick, 2010) suggests that in free choice environments individuals will select tasks to minimize cognitive effort, analogous to the "law of less work," which generally applies to physical exertion but can be extended to cognitive effort as well. When subjects select less complex lists in the task span procedure but not to the same degree in the memory span procedure, we can infer that their choice is biased towards less effort more often when the tasks actually have to be completed.

In considering the correlational data, our results indicated that working memory capacity was related to choice in the task span, but not the memory span. This finding can be explained in the context of differences between simple and complex working memory span tasks. Simple span tasks such as the digit span require participants to encode and retrieve a list of items without a secondary processing component. The complex span tasks such as the OSPAN require a further processing component along with item memory. A meta-analysis and review of the extant research on this distinction has indicated that simple span tasks with no processing component and complex span tasks largely measure the same underlying constructs of rehearsal, maintenance, updating, and controlled search (Unsworth & Engle, 2007). However, these tasks differ in the extent to which each of these components is required. The OSPAN is the canonical representation of a complex working memory span task. In the current paradigms, the voluntary task span has distinct processing and storage component, not unlike the OSPAN. The voluntary memory span is more similar in character to a simple span task. It is not surprising then that working memory capacity as measured by the OSPAN was related to choice in the task span but not the memory span in light of this difference between the two types of memory tasks. This difference in the relationship between working memory capacity in the task span and memory span may relate to the difference between choice in the two span tasks and the role of cognitive effort. Perhaps subjects with lower working memory capacity are also those who are least likely to break the "law of less work" because the more complex sequences are more daunting than those with greater structure or fewer switches.

Considering the choice data, executive control capacity showed the predicted correlation to participants' sequence selection bias in the memory span and the task span. Past research using the ANT to examine executive control in the context of a voluntary task switching experiment concluded that task choice was significantly related to the executive control measure (Arrington & Yates, 2009). Our results were consistent with this finding. Those participants with more efficient executive control networks were able to adhere more closely to the instructions to try to execute each sequence equally often. Interestingly this correlation was significant for the memory span as well as the task span. This suggests that what is being measured by the executive control score in the ANT may not just be related to the control engaged when needing to switch between tasks. Indeed the conditions that go into the measure of executive control in the ANT suggest that the ability to resolve response conflict may be the key process measured in this comparison. The relationship between the executive control score and sequence selection may suggest that at the time of sequence generation subjects may need to overcome activation of a previous response to the prompt in order to select the alternative response indicating a switch in task.

Our results indicating that working memory capacity is related to sequence choice in the task span but not the memory span, and that the executive control is related to choice in both conditions do not allow us to make definitive conclusions about the hypotheses outlined above. Most simply, we can conclude based on the current experiment that execution of the task span is dependent on both working memory and executive control resources, and execution of the memory span is dependent at least on executive control.

In addition to considering the relationships between choice and the individual differences measures, it is necessary to examine correlations with task performance. Results of correlations between working memory capacity and participants' choice and performance in the task span and memory span were not entirely consistent with past research that has investigated the role of working memory capacity in the voluntary task switching paradigm (Butler, et al., 2011). Butler, et al. found that task choice was unrelated to working memory capacity, whereas task performance in terms of the switch cost was related to this capacity. Our results that task choice was significantly related to working memory capacity in the task span may be attributable to differences in the way participants choose sequences for the voluntary task switching paradigm compared to the voluntary task span paradigm. In voluntary task switching, participants may select tasks in an online manner as targets appear, whereas in the task span participants must load their working memory at the start of each block of trials with their task switching sequence—a very different requirement. This explanation is also applicable to the difference in the relationship between working memory capacity and the switch cost. Higher working memory capacities may have related to switch costs in the voluntary tasking switching paradigm because participants had to retrieve task set representations from long term memory in an online manner, a requirement that relies on the ability to efficiently manipulate information in working memory. This may not have been a requirement in the task span paradigm, as participants had a stored plan for task switches that may have allowed for the same sort of advanced preparation for upcoming task switches. These distinctions likely played a part in why we see this difference in the relationship of task choice and performance and working memory capacity.

Experiment 1 was conducted in an attempt to use naturally occurring individual differences as a sort of fine-grained manipulation of the constructs of working memory and executive control. The results of this experiment indicated that these two factors are significantly related to participants' performance and choice when they are in volitional environments that require sequence planning and execution. Participants' planning, recall, and execution of simple sequences of actions is a surprisingly complex endeavor, dependent on many individual difference factors and sensitive to many characteristics of the list patterns. Such a relationship between these executive control and working memory capacity individual difference measures and task choice and performance begs the question of whether manipulating these constructs experimentally will have an impact on performance response times, memory, and sequence choice when individuals are planning sequences of actions for later recall or execution. Manipulating working memory and executive control can tell us about how experimenter-driven factors influence sequence choice, which is not available when simply correlating already-present endogenous differences. Manipulations of these two factors were the focus of Experiments 2 and 3.

Experiment 2

Results of Experiment 1 suggested that participant's working memory capacity is highly correlated with their choice and performance in the voluntary task span procedure. Experiments 2 and 3 were designed to determine if a load on these cognitive systems yields results that align with the individual differences relationship discussed in Experiment 1. This manipulation of load was designed to toll working memory in conjunction with Oberauer's (2010) model, which includes a procedural and a declarative component. As a reminder, the declarative component of working memory according to this model is responsible for maintaining information that is able to be manipulated or recalled at will, such as lists of letters or numbers. The procedural component of working memory according to the model is responsible for maintaining information that would allow for an individual to actually carry out tasks related to some predetermined criteria. For example the procedural component might be responsible for remembering things like task sets, or plans and rules for later behavior.

For both types of working memory in this load manipulation, participants need to maintain information throughout the duration of the task span. What differs between each condition is the nature of the information; the declarative condition requires participants to maintain a single item, and the actual task they carry out does not vary. In the procedural condition participants maintain a task-relevant instruction upon which their action performance depends.

Methods

Participants. Participants included 16 Lehigh University undergraduates who participated in exchange for partial class credit. All participants had normal or corrected to normal vision and signed a document indicating their informed consent to participate in the experiment.

Stimuli and Procedure. Stimulus presentation and response recording were controlled by E-Prime software (version 2.0) running on Dell Optiplex computers with 17 inch flat panel monitors. The experiment consisted of the administration of the voluntary task span and voluntary memory span procedures. In conjunction with completion of the task span and memory span procedures as in Experiment 1, participants were also given an additional working memory task. Half of the trials included a task that was intended to load the declarative component of working memory, and half of the trials included a task that was intended to load the procedural component of working memory. This working memory load was manipulated within-subjects.

For the declarative task, participants were presented with a single letter at the beginning of each trial for 1000ms, and instructed to remember it throughout the implementation of the task or memory span, which were identical to the procedures from earlier experiments. The letter was one of F, H, J, K, L, N, P, or Q. Following the completion of task performance or recall, participants were presented with a final screen to complete the working memory load portion. Two outlined boxes were present on the left and right sides of the computer screen. One box contained the letter that the participants had originally seen at the beginning of the trial, the other contained a different letter that they had not seen during that trial. Participants pressed the arrow key corresponding to the side of the screen which the previously viewed letter was presented on. The recall screen was presented until the participant gave a response. For the working memory load, every trial included the manipulation.

For the procedural task, participants were presented with an instruction at the beginning of each trial, and were asked to remember it while they implemented the task or memory span. This instruction was either “same” or “opposite”, which was used to instruct the execution of a directional movement (similar to a pro- or anti-saccade task) at the end of the trial. Each block began with an instruction screen with one of the words “same” or “opposite” present on the computer monitor for 1000ms before the beginning of the span procedure. Following task performance, participants were presented with two outlined boxes on the right and left sides of the screen, one of which contained an asterisk. Based on the previously viewed instruction, they were told to press the arrow key that corresponded to the side of the screen presenting the box containing the asterisk, (pro-directional movement) or press the arrow key corresponding to the side of the screen with the empty box, which was on the opposite side of the screen from the asterisk (anti-directional movement). The instruction of "same" was paired with the pro-directional movement, while the instruction of "opposite" was paired with the anti-directional movement.

Response time for the cues and targets was recorded, as well as target accuracy in the task span and task memory in both conditions. Participants carried out 60 blocks of the task span and 60 blocks of the memory span. 30 blocks in each condition involved the declarative task, while 30 blocks involved the procedural task. Task order was counterbalanced between subjects.

Results

Analyses in Experiment 2 were based on data from 14 participants. Significance testing was performed at $\alpha = .05$.

Voluntary Task and Memory Spans

As in Experiment 1, data were trimmed to eliminate trials on which participants made errors in responding to the target, as well as the trials following these errors as they were significantly slowed. Trials for which response times were lower than 150ms or greater than 4000ms were also eliminated from analysis. Elimination occurred only for the specific trial where the error or response time violation occurred, not for the entire list. Target accuracy was very high, 93%.

Performance and Choice. The same analyses were calculated as in Experiment 1, with an additional independent variable separating control participants from those who received the working memory load manipulation. Because the control group in this experiment was the group of subjects from Experiment 1 who completed the voluntary memory span and voluntary task span with no working memory load, and because the group of subjects in Experiment 2 was quite small compared to the control group, the significant main effects of the independent variables did not change from Experiment 1. They are therefore not reported again here. The issue of heteroscedasticity of variance between these two groups was considered: while there were violations of the homoscedasticity of variance assumption in many cases, decisions about significant effects were not impacted by corrections for these violations and therefore they were not applied.

These analyses outline the interactions of the independent variables with the experimental condition of which participants were a part. Serial position (6 levels), transition—presented in Appendix B, (2 levels), switch value (5 levels) and complexity score—presented in Appendix B, (4 levels) were within-subjects factors, as was the span condition (task span or memory span). Experimental condition was a between-subjects factor. As in Experiment 1, main results (those related to hypotheses) are presented here, while additional analyses are presented in Appendix B.

Target Response Times. The working memory load did not impact the time it took participants to respond to targets. This conclusion was supported by the results of repeated measures ANOVAs. There were no significant interactions of task transition or switch value, with experimental condition on target response times, all *F*s < 1.611, all *p*s > .208. There were no three-way interactions.

List Memory. There was a significant interactions between switch value $F(4, 280) = 4.372$, $p = .002$, with experimental condition on memory for lists. There were no three way interactions. Lists with greater numbers of switches had lower memory in the load condition than in the no-load condition, seen in figures 6 and 7. Simple main effects tests indicated that list memory was significantly impacted by switch value in both the task span, $F(4,336) = 34.559$, $p < .001$, and the memory span, $F(4,316) = 16.23$, $p < .001$, separately. Higher switch values resulted in lower memory for lists in all conditions.

Choice. Comparing choice in the task span (figure 8a) across experimental conditions indicated that there was no significant differences between participants' patterns of choice as measured by their deviation scores, $t(96) = 1.573$, $p = .119$. There was, however, a significant difference in participants' choice in the memory span (figure 8b) between experimental conditions, $t(93) = 2.363$, $p = .02$. Participants under the working memory load had a greater tendency to choose less complex sequences than those not under load. When analyzing participants' choice patterns as a function of the complexity of the sequences, there was a significant interaction between the choice score and the experimental condition, indicated by a one-way ANOVA, $F(3,192) = 5.496$, $p < .001$. Post-hoc tests indicate that this effect comes from a difference between participants choice in the memory span between conditions, $t(93) = 2.36$, $p = .02$. Participants in the working memory load condition of the memory span chose the more complex sequences less often than those in the no-load condition.

Declarative and procedural component analysis. An additional question of this experiment was if manipulations of the declarative and procedural components of working memory would have differential impacts on participants' performance. Choice behavior was not analyzed because there were too few blocks in each condition to calculate a reliable measure. Performance in this experiment was compared across the two different manipulations to determine if these conditions differed from each other. There were no significant differences except in memory for lists. An outline of additional null effects is present in Appendix B.

Target Response Times. There was no difference in the way participants responded to targets when comparing the two load manipulations—procedural and declarative working memory. Target response times did not vary as a function of position in the list differently between the two manipulations, nor as a function of transition, switch value, or complexity score, all Fs < 2.269, all ps $> .098$.

List Memory. There was a small difference in the way the number of switches in a list affected participant's memory for entire lists. The switch value of a sequence had a marginally significantly different effect on memory for lists between the declarative and procedural working memory manipulations, $F(4,28) = 2.406$, $p = .073$. As the number of switches in the list increased, the list memory decreased more for procedural working memory than for declarative working memory. Tests of simple main effects indicated that there was a somewhat smaller effect size for the declarative manipulation, $F(4,36) = 8.965$, $p < .001$, $\eta^2 = .49$, than for the procedural manipulation, $F(4,36) = 7.57$, $p < .001$ $\eta^2 = .52$

Discussion

This experiment included a manipulation of working memory load while participants completed the memory span and task span used in the previous experiment. We included a manipulation of each of Oberauer's (2010) two components of working memory, the declarative sub-system and the procedural sub-system. Our goal was to determine if an experimental treatment of the working memory construct would impact participants' choice and performance in the same way that naturally-occurring individual differences affected these variables in Experiment 1. Overall the results suggested that there were differences between participants' choice behavior and performance when they were holding a working memory load compared to when they did not have a load. Specifically, memory performance decreased when participants were under the working memory load. There was also increased deviation from ideal choice patterns in the memory span, with participants under load choosing the more complex sequences less often.

There were, however, almost no differences in the way that participants chose sequences and performed them in relation to sequence characteristics between the two different types of working memory load. We expected that the contrast between holding a letter in mind for later recall and holding an instruction in mind for later implementation would be appropriate for a manipulation of the declarative and procedural components of working memory respectively. Results that these two manipulations did not have different effects on participants' performance may suggest that these manipulations were not effective in separately loading these different aspects of working memory as we intended. These two manipulations may have both loaded the declarative portion of working memory, as participants may not have represented our instruction as procedural information.

Examining the two types of load together indicated that participants' memory and choice were negatively impacted by having the extra information to hold in working memory while carrying out the task span or memory span. Choice behavior was different for the memory span and the task span—supporting the findings from Experiment 1, which suggested that these processes are undertaken in different manners. There is something special about having to actually carry out the memorized tasks in the task span, which explains our previous results, but the execution of the task span was not impacted by a load on working memory whereas the memory span was. Perhaps this result comes from the already quite distinct choice differences between the memory span and the task span. Since choice was already so biased in the task span, there would be less room for a difference between experimental conditions to be evident. Since choice was not as biased in the memory span, there is more opportunity for this bias to show up between the experimental conditions. It is also possible that the information stored in working memory was more similar to the way participants stored tasks in the memory span than in the task span. If the way this information was stored loads onto the same resource for the working memory load and the memory span, perhaps declarative working memory is the resource, we would expect the results we found of more biased choice only in the memory span. This possibility is examined in more depth in the General Discussion.

Experiment 3

Experiment 3 included a cognitive load manipulation, which required participants to engage in a secondary monitoring behavior while also carrying out a primary task. The primary task was the implementation of the task span and memory span paradigms, which they completed one at a time. This monitoring behavior required the exercise of executive control, as participants had to monitor for additional stimuli and coordinate their responses within this more demanding environment. This additional experiment allowed us to manipulate the availability of executive control processes, and measure participants' choice behaviors under load compared to no load conditions.

Methods

Participants. Participants included 16 Lehigh University undergraduates who participated in exchange for partial class credit. All participants had normal or corrected to normal vision and signed a document indicating their informed consent to participate in the experiment.

Stimuli and Procedure. Stimulus presentation and response recording were controlled by E-Prime software (version 2.0) running on Dell Optiplex computers with 17 inch flat panel monitors. The aspect ratio was adjusted to be the consistent with the monitors used in Experiment 1.

The experiment consisted of the administration of the voluntary task span and voluntary memory span procedures described previously, with the inclusion of a manipulation of executive control processes. This was achieved by including a secondary task that participants carried out while also maintaining adequate performance of the primary tasks. This secondary task involved monitoring for the presence of an auditory tone. On a pseudo-randomly selected minority of trials (20%), a tone was played, either a high or low frequency. The high frequency tone was 1000hz, and the low frequency tone was 200hz. Each tone was presented for 500 ms. Tones were presented after the second or fifth prompts during the generation phase, or at any point during the stimuli presentation in the test phase. Participants responded to either the high or low tone by pressing the Enter key. To which tone (high or low frequency) the participant responded was counterbalanced among subjects.

The tone was played variably throughout the entire trial progression, either at generation or performance/recall. After the presentation of the tone, the participant had 1250 ms to make his or her key press. Following either the key press or the complete 1250 ms post-tone period, there was a 500 ms interval before the next prompt or target appeared on the screen. Regardless of the part of the block during which the tone occurred, the remaining prompts and targets were presented normally.

Response time for the cues and targets was recorded, as well as target accuracy in the task span and task memory in both conditions. Participants carried out 60 blocks of the task span and 60 blocks of the memory span. Task order was counterbalanced between subjects.

Results

Analyses in Experiment 3 were based on data from 14 participants. Significance testing was performed at $\alpha = .05$.

Voluntary Task and Memory Spans

Data were trimmed in exactly the same manner as Experiments 1 and 2, to eliminate trials on which participants made errors in responding to the target, as well as the trials following these errors as they were significantly slowed. Trials for which response times were lower than 150 ms or greater than 4000 ms were also eliminated from analysis. Elimination occurred only for the specific trial where the error or response time violation occurred, not for the entire list. Target accuracy was 91%.

Performance and Choice. The same analyses were calculated as in Experiments 1 and 2, with the included independent variable of experimental condition. The control group in this experiment was the same group of subjects from Experiment 1 who served as a control group for Experiment 2. Therefore the additional interactions between the independent variables and the experimental condition are the only analyses presented here. Corrections for heteroscedacity of variance between the two groups are not presented because they did not impact decisions of significance for any effects.

These analyses outline the interactions of the independent variables with the experimental condition participants were part of. Serial position—Appendix C, (6 levels), transition (2 levels), switch value (5 levels) and complexity score—Appendix C, (4 levels) were within-subjects factors, as was the span condition (task span or memory span). Experimental condition was a between-subjects factor. As in the previous experiments significant results related to hypotheses are presented here; additional analyses are presented in Appendix C.

Preliminary Analyses. Overall there were no differences between participants' performance in the dual-task condition compared to the single-task condition. This was true for the prompt response times $t(94) = .578$, $p = .439$, target response times, $t(94) = .298$, $p = .767$, list memory, $t(94) = -1.044$, $p = .299$, and task memory, $t(94) = -.993$, $p =$

.323. These effects are considerably different when examined with regards to each independent variable, described below.

Target Response Times. In general, target response times were faster in the executive control manipulation condition than in the control condition. This was evident when this dependent measure was examined as a function of the local measure of task transition. Switch costs were smaller for the target responses in the dual-task condition compared to the control condition. There was no significant difference in the effects of complexity or switch value on target responses between the two experimental conditions. These findings were supported by the results of mixed factors ANOVAs. There was a marginally significant interaction of task transition and experimental condition on target response times, $F(1,85) = 2.954$, $p = .089$, repetition trials were longer and switch trials were shorter in the dual-task condition than in the single-task condition. There was no significant interaction between switch value, $F(4, 280) = .772$, $p = .544$, and experimental condition on target response times. There were no three-way interactions.

List Memory. List memory was not affected by the manipulation of executive control in this experiment. Participant's memory for entire lists did not vary based on their experimental condition. Based on the results of a RM ANOVA, we concluded that there was no significant interaction of switch value, $F(4, 280) = .726$, $p = .574$, and experimental condition on memory for lists.

Choice. Overall, participants under the executive control manipulation did not deviate from the ideal equivalent sequence pattern in a different way than those not under any manipulation for the task span condition. Comparing choice in the memory span and task span across experimental conditions indicated that there was no significant interaction between participants' choice deviation scores when they were undergoing the executive control manipulation compared to the control condition for the two span conditions, $F(1,84) = .405$, $p = .526$ (memory span seen in figure 9a). Analyzing choice data as a function of the complexity of sequences, with the span condition and experimental condition as factors, however, indicates that there is a significant difference in the complexity of sequences chosen across all span and experimental conditions, supported by a one-way ANOVA, $F(3,190) = 18.615$, $p < .001$. Post-hoc tests reveal that this significant effect comes from a difference between choice patterns in the task span between the two experimental conditions, $t(94) = 8.053$, $p < .001$. Participants in the dual-task condition, seen in figure 9b, chose the more complex sequences less often than participants in the control condition.

Discussion

This experiment included a manipulation of executive control, implemented as a dual-task paradigm with the memory span and the task span occurring with a concurrent tone-monitoring task. Our results indicated that there were few differences in participants' performance across the task span and the memory span when comparing the dual task condition to the single task condition. The only real difference in performance between conditions was that response times to targets in the dual-task condition were actually faster on average than in the control condition, and switch costs were smaller. This result is surprising, as we would expect a load on executive control to slow down performance and result in larger switch costs if there would be any effects at all. There was a significant difference between choice patterns in the dual-task and control conditions, in the expected direction, with a greater bias for the less complex sequences in the dual-task condition.

Based on the results of Experiment 3, it is difficult to say whether our manipulation of executive control was effective. The largest pieces of evidence suggesting that it was not comes from the faster task performance and recall, coupled with smaller switch costs in the dual-task condition. Repetition trials were slower and switch trials were faster in the dual-task condition, resulting in a smaller switch cost, and overall responses were faster when participants were engaged in the dual-task manipulation than when they were not. These results are very contrary to our predictions. An effective manipulation of executive control should have made switching tasks more difficult, resulting in longer response times at least for switch trials, and likely overall as well. An explanation for these results is that there were significant differences between the participants in the two conditions. Because we did not have a within-subjects control, it is possible that the differences we observed may be a result of an overall difference between groups, rather than an effect of the manipulation. Alternatively, and more interestingly, it is possible that our results suggest participants held a weaker task set representation when they underwent the dual-task procedure. Less of a priming effect on repetition trials, and less interference on switch trials could indicate that the task set was not as strongly instantiated in the dual-task condition as it was in the control condition, which could happen under such an executive control load.

Despite the uncertain results of task performance, we did find a promising difference in choice behavior between the two conditions. Participants in the dual-task condition were less likely to choose the more complex sequences when compared to those in the control condition, for the task span only. This suggests that there was some effect of this dual-task load when participants had to execute the sequences they generated, but not when they were only recalling the lists. Perhaps the demand of task execution was interrupted more easily by the presented tone than was simply recalling, which affected participants' likelihood to choose sequences that were harder to remember and execute on their own.

It is interesting that we found differences between the dual-task and control conditions for task choice but not task performance. The greater variability in sequence choice in Experiment 1 compared to the current experiment may be the direct cause of longer response times to targets in that no-load condition. Participants did more of the more complex sequences in that case and therefore naturally got less practice in the simpler sequences. In the current experiment, perhaps participants benefited from practice effects, resulting in the smaller switch costs and faster response times to targets we see here. This explanation might lead us to believe that the manipulation was successful, and an impact on choice is more telling of the processes occurring to support the behavior necessary in the task span than simple performance data is.

Experiment 1 indicated that executive control ability as measured by the ANT was significantly related to choice in both the memory span and the task span, but Experiment 3 only found a relationship between executive control load and choice in the task span. This finding can be explained by considering that the executive control capacity measured by the ANT may not tap into the same aspect of this construct as our manipulation impacted. The ANT measures individuals' abilities to overcome response conflict. Our manipulation of executive control may have tapped more into the ability to monitor multiple streams of information, and to inhibit inappropriate responses when the tone presented did not warrant a response. Indeed these components of executive control have been shown to be separable, although they are moderately correlated with one another (Miyake, et al, 2000). If this is the case, then it is not surprising that the memory span was related to executive control as measured by the ANT but not impacted by this manipulation. As described in the discussion of Experiment 1, the ability to resolve conflict may have to do with the ability of participants to overcome the activation of previous responses when generating sequences, allowing for switches in tasks and more complex overall lists. This difficulty would affect the task span and the memory span alike. Monitoring may be another facet of this executive control construct that does not interfere with the recall of sequences but does interfere with the execution of tasks, resulting in a different impact on choice between the two conditions, as we found here.

General Discussion

Three experiments were conducted with the goal of examining the connection between executive control, working memory, and individual's abilities to plan out sequences of action for later implementation. Experiment 1 included measures of individual's working memory capacity, (the automated OSPAN), executive control ability (ANT) and the voluntary task and memory spans. Experiment 2 involved the voluntary task and memory span procedures, as well as a manipulation of a working memory load, which was developed with the intention of taxing procedural and declarative working memory, as defined by Oberauer (2010). Experiment 3 also included the two voluntary span tasks, as well as a manipulation of executive control using a dual-task paradigm. Overall results were consistent with past research (Reiman, et al., in prep.), in that increased complexity and number of switches in a sequence decreased participants' performance, and also the likelihood they would choose to execute those sequences. These effects were greater in the task span than in the memory span. This difference between the two span tasks tells us something about how individuals are making choices about what tasks to implement. The additional requirement of task execution in the task span is challenging enough that it slows participants' performance, and biases them away from choosing complex sequences. Participants have a bias to limit their cognitive effort, and this bias is intensified when their task itself is more complicated, as in the task span.

Performance and choice in the task and memory span procedures showed a pattern of correlations with OSPAN scores, which index individuals' abilities to maintain and process information in working memory, and with executive control scores from the ANT, which index their ability to resolve conflict. The main findings indicate that greater ability to resolve conflict was associated with participants' choice in both the task span and memory span. From these correlations we can infer that choice behavior when planning sequences of actions is dependent upon executive control resources, regardless of how these sequences will be implemented. This connection may be a result of the need to overcome activation of previous responses when generating sequences, which would rely on the ability to resolve conflict as measured by the ANT. Greater working memory capacity was correlated with choice only in the task span. We suggested that this relationship may be a result of the similarity between the task span and the complex span task we chose as a working memory measure, the OSPAN.

The manipulations of working memory load and executive control implemented in Experiments 2 and 3 yielded mixed results. Overall the results suggest that there was some success with the manipulations, but it is unclear whether they tapped into the exact constructs we were intending, particularly for the working memory load in Experiment 2. We did find a promising effect that overall diversity in sequence choice was diminished in the manipulation experiments, but sequence performance was less conclusive. It is clear from these experiments that these constructs are important to choice behavior when planning out sequences of actions, as loading onto these resources diminishes choice in such a way that participants are biased towards lower complexity. Further research can address the limitations of these manipulations to more effectively, and perhaps more strongly, load onto these mental resources.

Task Span

Past research using the task span paradigm has focused on the ways the task span is related to executive control and working memory, and how individuals are able to implement planned series of actions (Logan, 2004; 2006; 2007). The current study as well as my past research (Reiman, et al, in prep.) has expanded on Logan's work in some empirically interesting ways. We have examined the processes involved in encoding sequences for later action, and allowed individuals to generate their own sequences in an effort to examine volitional behavior when planning later actions.

Logan has suggested that the task span paradigm is a test of the "endogenous act of control" (2004, p. 234). The original motivation for the use of this paradigm was to avoid the limitations of other commonly used task switching paradigms, such as the alternating runs and explicit task-cuing procedures. In the task span, individuals must precisely control the memory load of the span, and recall which task to perform on their own. Our research imposes an additional demand on executive control, namely the endogenous generation of task span sequences. Not only must participants monitor their performance on a block by block basis, but they must also monitor their performance across the experiment, in order to follow our instructions to try to do all sequences equally often and in an unpredictable manner. (Although the demands of this cross-experiment monitoring probably varied widely across participants depending on the level to which they tried to follow the instructions).

Results of Logan's first task span study (2004) indicated that there are separate processes that underlie storage and processing, which was determined based on the lack of a trade-off between performance in the task span and basic memory span. Our results may be consistent with this claim in the context of volitional sequence selection. In the current experiment, choice was quite different in the memory span and the task span, indicating that there are differences in how the demands of those tasks influence the likelihood a variety of sequences will be implemented. Sequence characteristics such as complexity also influenced choice in the memory span and task span differently, and together these findings support the idea that storage and processing do not rely on the same mechanisms.

Voluntary Task Switching

Past research using the voluntary task switching paradigm has demonstrated that many factors, both endogenous and exogenous, play large roles in determining how individuals will select tasks for execution. Working memory load (Weaver, & Arrington, 2010), individual differences in working memory capacity (Butler, et al, 2011), and executive control (Arrington & Yates, 2009), and advanced preparation for task performance (Arrington, 2008) are all factors that can endogenously influence choice and performance when selecting tasks. The onset asynchrony of task presentation (Arrington, 2008), stimulus repetition (Mayr & Bell, 2006) or task difficulty (Yeung, 2010) are examples of exogenous influence on task selection.

The overarching theme of these combined avenues of research is clear about one thing: volitional behavior when selecting tasks is never based exclusively on endogenous or exogenous factors. There is always a dynamic interplay of these two types of influence on behavior, which can lead to the repetition biases and performance costs typically observed in voluntary task switching. The current studies demonstrated that voluntarily planning out sequences of tasks to execute and recall is similarly influenced by both exogenous and endogenous factors. Individual differences in working memory capacity and executive control were shown to influence task choice and performance, and manipulated loads on these resources also influenced what sequences participants selected. This finding has ecological validity, as the volitional planning of action outside of laboratory settings is correspondingly dependent on the interplay of external constraints on behavior and internal goals.

Chain-retrieval model. A model of choice behavior in voluntary task switching has recently been developed to explain the repetition bias commonly seen in voluntary task switching experiments (Vandierendonck, Demanet, Liefooghe, & Verbruggen, in press). It was based on established models of random generation, as the authors determined that the process of randomly selecting tasks for execution in voluntary task switching is analogous to that sort of random generation, only with the addition of actually having to carry out the tasks. These foundation models of random generation focus on retrospective monitoring and correction of sequences, whereas the voluntary task switching selection model focuses on prospective choice, which is able to account for the difficulty of actually switching tasks and include this information in the predicted choice patterns. This chain-retrieval model, as it has been named, assumes that short chains of task sequences are stored in long term memory, and are retrieved and selected based on certain characteristics to guide choice behavior.

The model includes three free parameters. The first, *m*¸ is based on the participant's working memory capacity. The second, *p*, is related to the strength of the chain, which can be interpreted as the ease of the chain of tasks in terms of implementation; larger values of *p* indicate more repetitions. The final parameter, *r*, is related to bottom-up priming, or the probability that a repetition will intrude on a sequence.

This model explicitly states that working memory capacity will constrain task choice. The results of the current experiments support this claim. Experiment 1 indicated that working memory capacity was significantly correlated with sequence choice in the task span, and those with higher capacities were more likely to choose to execute all of the possible lists in a more balanced manner. Loading working memory also diminished the diversity of sequence choice.

Vandierendonck and colleagues indicate that if the participant is not required to execute the tasks he or she is choosing, the *p* parameter, ostensibly the ease of the chain, should become irrelevant. When participants do not have to execute tasks, then the ease in which execution would take place does not matter. This assertion leads to the prediction in the current paradigm that if tasks do not have to be executed, then the tendency to choose less complex sequences would be less strong. This claim is supported by our data. Task choice in the memory span, when tasks did not have to be executed, was less biased than in the task span.

Our results provide additional support for this chain retrieval model, and the model is also useful in explaining our data. This model of task choice was designed to account for the repetition bias seen in voluntary task switching, which is analogous to the simple-sequence bias we observed in the task and memory spans. Exploring the parameters of this model provides an account of our findings, particularly those relevant to choice when planning out sequences of action. The chain-retrieval model is applicable to situations where tasks are represented as their task names (i.e. height or shape) and also when they are represented as transitions (i.e. switch or repeat). Future research can address this question of how tasks are represented in voluntary task switching, and also in the task span.

Declarative and Procedural Working Memory.

Oberauer’s (2010) discussion of the differences between procedural and declarative working memory bears a similarity to the differences between the task span and the memory span used in the current experiment. In the task span, participants must hold task sets in working memory and continuously monitor and update actions to reflect which task they are currently working on. These requirements are directly in line with the procedural working memory tasks outlined in his model. Based on this analyses, an effect of loading procedural memory in Experiment 2 on performance in the task span was predicted and would have provided evidence for this relationship between this system and behavior in the task span. Our data did not support this relationship. It is possible that our load manipulation did not actually load onto procedural working memory as planned, but rather onto declarative working memory. Oberauer indicates that task instructions can load onto declarative WM if they are not represented as task sets or procedures. This proposition is more consistent with our results. A stronger manipulation of procedural working memory would be beneficial in the future, to support this claim that the task span is a procedural working memory task.

This potential connection is contrasted with the requirements of the memory span, which is likely reliant on the component of the declarative working memory system. In the memory span, participants have to hold pieces of information in mind and simply recall them with little monitoring or updating, which is exactly the sort of circumstances under which declarative working memory would be active. Evidence for this claim that the memory span is a declarative working memory task would come from decreased performance in the memory span when the declarative sub-system is under load. We did see this in Experiment 2. When participants were under working memory load (assuming that both of our tasks loaded onto declarative working memory), their task choice variability decreased in the memory span. This is support for the idea that the memory span is a declarative working memory task.

Oberauer describes the two sub-systems of declarative and procedural working memory as similarly organized systems that contain comparable components. He suggests that these two sub-systems behave similarly in response to stimuli, but that the characteristics of those stimuli and the specifications of each system vary. To the extent that the task span and the memory span are procedural and declarative working memory tasks, respectively, our results support these claims. The sequence characteristics based on which we analyzed the data, such as complexity, task transition, and serial position, all had similar effects on performance and choice in the task span and memory span alike. There are some exceptions to this claim, such as the different effects of serial position on task recall and task performance, but in general the sequence characteristics affect performance quite similarly across the two types of spans. Overall, Oberauer's model fits quite nicely with our data. The memory span and the task span are closely linked to the declarative and procedural sub-systems in his model, and provide support for his proposed working memory architecture.

Conclusions.

The results of the current three experiments have provided insight as to how individuals voluntarily plan and execute sequences of tasks for later execution or recall. Past research using the voluntary task span paradigm has investigated encoding processes, but there has not been investigation of how encoding differs when information will not be used for task execution. In fact the voluntary memory span has not been used at all in past research. With the inclusion of this measure we have learned that there are marked differences between choice and performance when selecting actions for later recall compared to later execution. Individuals are more willing to plan complex sequences when they will be used only for recall compared to when they will be used to guide actual task implementation, aligning with the idea that individuals make decisions with the goal of limiting cognitive effort. We have extended past research to explore the choice bias that has been seen in the task span paradigm, and determined that this bias is directly linked to the demands of these sequences on executive control and working memory. Our results speak to the factors that influence the planning and implementation of action sequences, and suggest that when planning behavior, it is all about limiting unnecessary cognitive effort.

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Table 1.

Possible Sequence Orders

Original Sequence	Opposite Sequence	Sequence Pattern	Number of Switches	Complexity Score
HHHSSS	SSSHHH	rrsrr	1	8
HHSSSH	SSHHHS	rsrrs	2	11
HSSSHH	SHHHSS	srrsr	2	11
HHSHSS	SSHSHH	rsssr	3	14
HHSSHS	SSHHSH	rsrss	3	14
HSHHSS	SHSSHH	ssrsr	3	14
HSSHHS	SHHSSH	srsrs	3	14
HSHSSH	SHSHHS	sssrs	4	11
HSSHSH	SHHSHS	srsss	4	11
HSHSHS	SHSHSH	sssss	5	5

Note: *H*—height, *S*—shape, *r*—repetition, *s*—switch

Table 2.

Summary of Correlations in Experiment 1.

	OSPAN Absolute Score	Executive Control Score
Memory Span Avg. Deviation	-.088	.267**
Task Span Avg. Deviation	-.278**	.291***
Task Span List Memory	.203*	.085
Memory Span List Memory	.207*	-.241**
Task Span List Memory as a Function of Switch Value	.207*	-.169
Memory Span List Memory as a Function of Switch Value	-.002	-.339***
Task Span Switch Cost	-.019	.232**
Memory Span Switch Cost	-.217*	-.022
Task Span Target RT	-.060	-.053
Memory Span Target RT	-.051	-.150
Task Span Prompt RT	-.082	.032
Memory Span Prompt RT	-.106	-.150

Note: * indicates $p < .10$, ** indicates $p < .05$, *** indicates $p < .01$

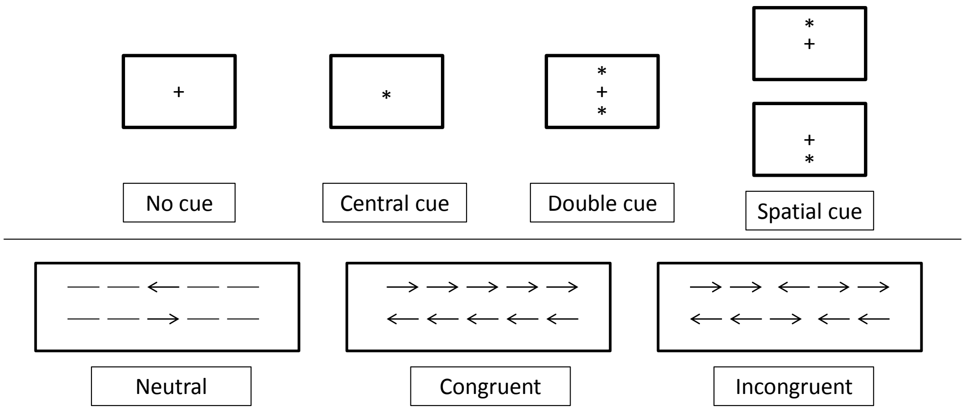

Figure 1. Adapted from Fan, McCandliss, Sommer, Raz & Posner (2002) depicting the cue and flanker alternatives in the Attention Networks Test.

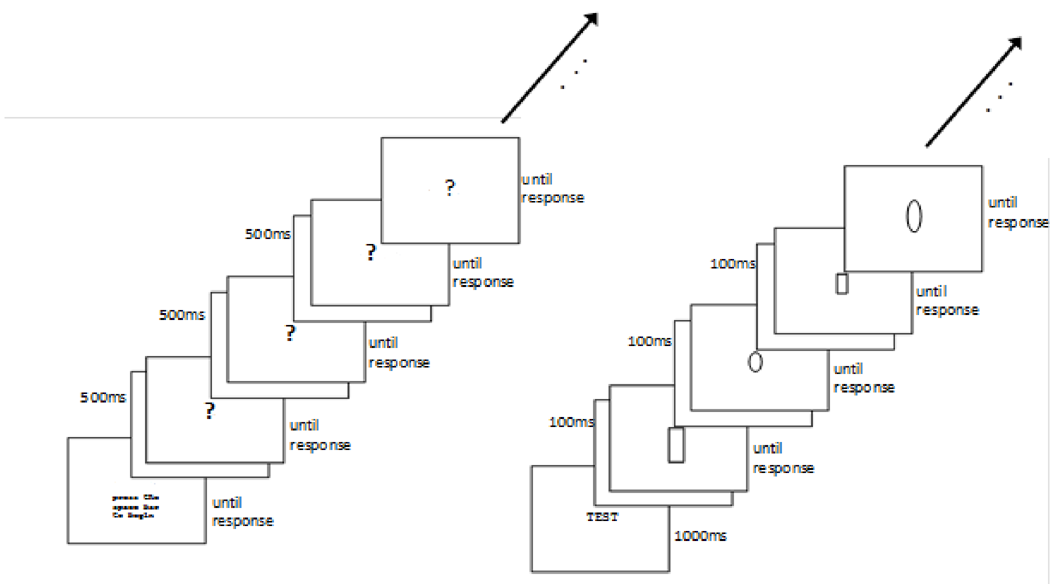

Figure 2. A depiction of the progression of the generation and test phases in the task span paradigm.

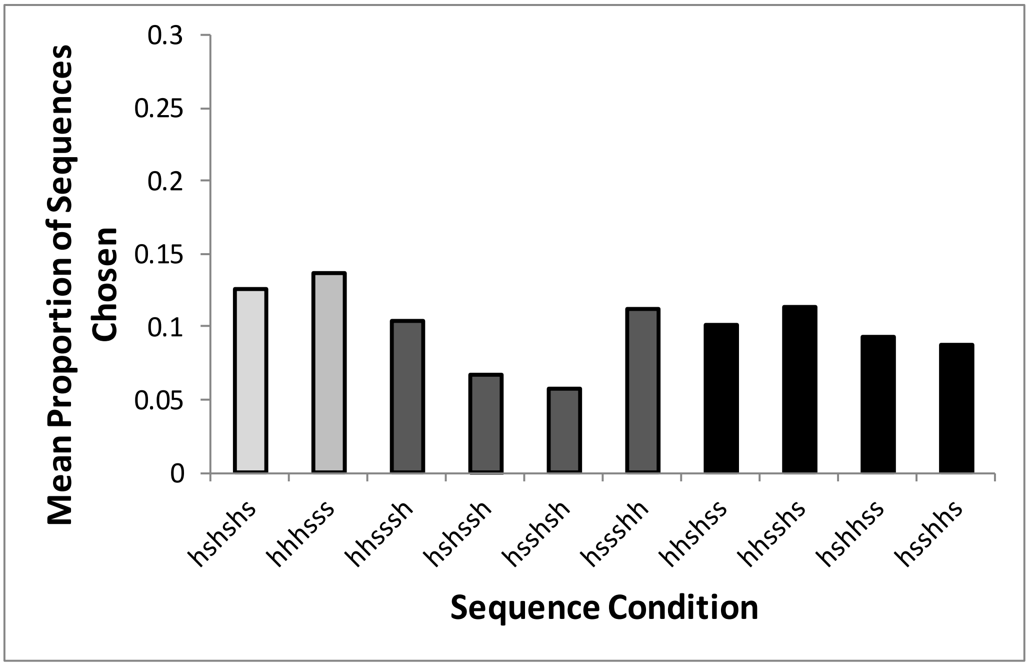

Figure 3a. The proportion of trials on which particular sequences were selected in the memory span for Experiment 1.

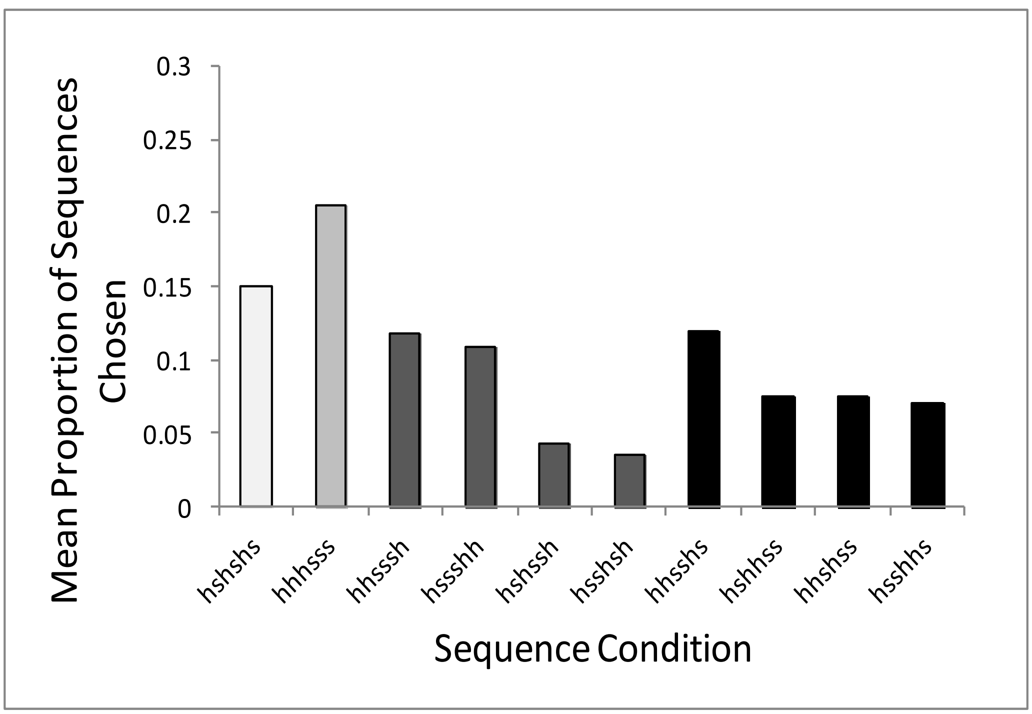

*Figure 3b.*The proportion of trials on which particular sequences were selected in the task span for Experiment 1.

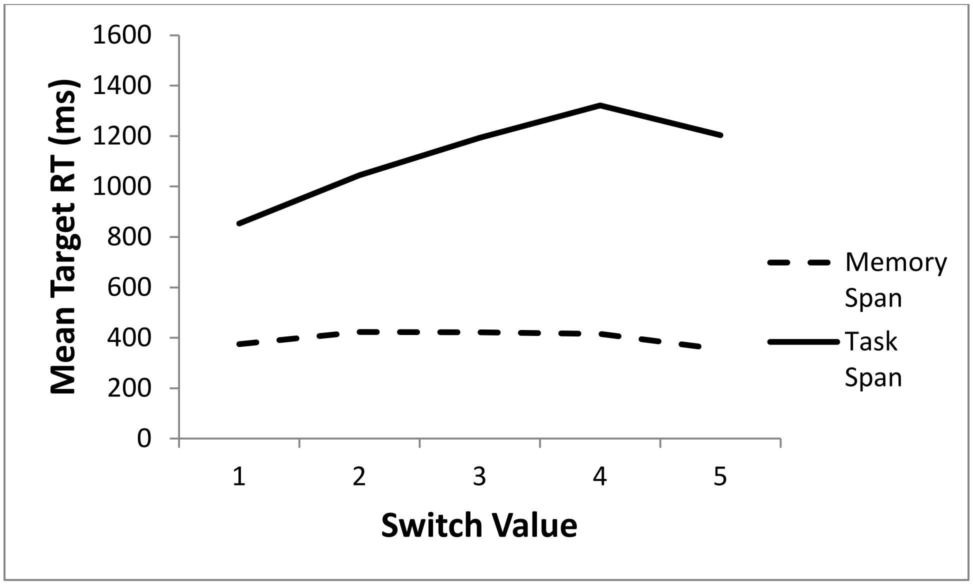

Figure 4. Mean response times to targets as a function of the switch value in Experiment 1.

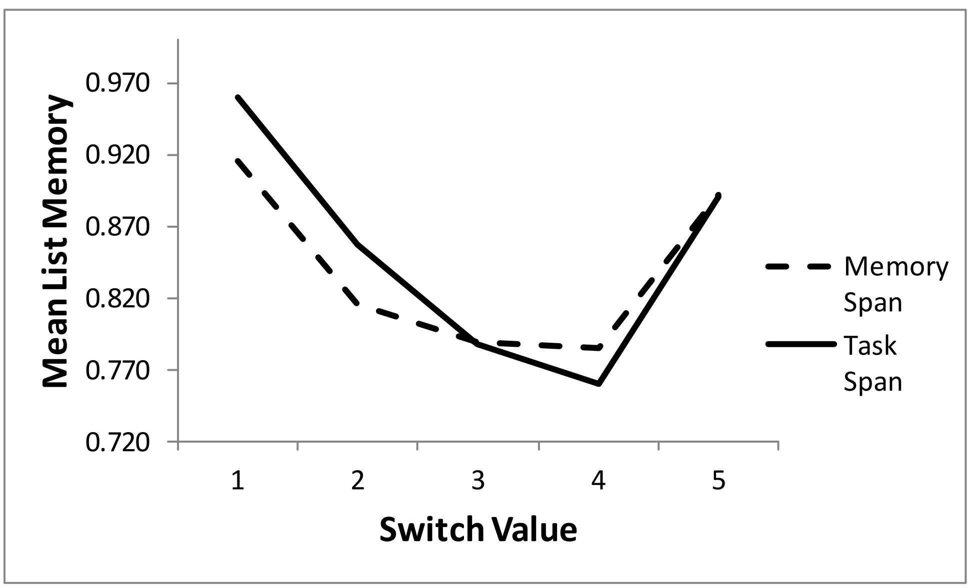

Figure 5. Mean percentage of lists accurately remembered in the task span and memory span as a function of switch value in Experiment 1.

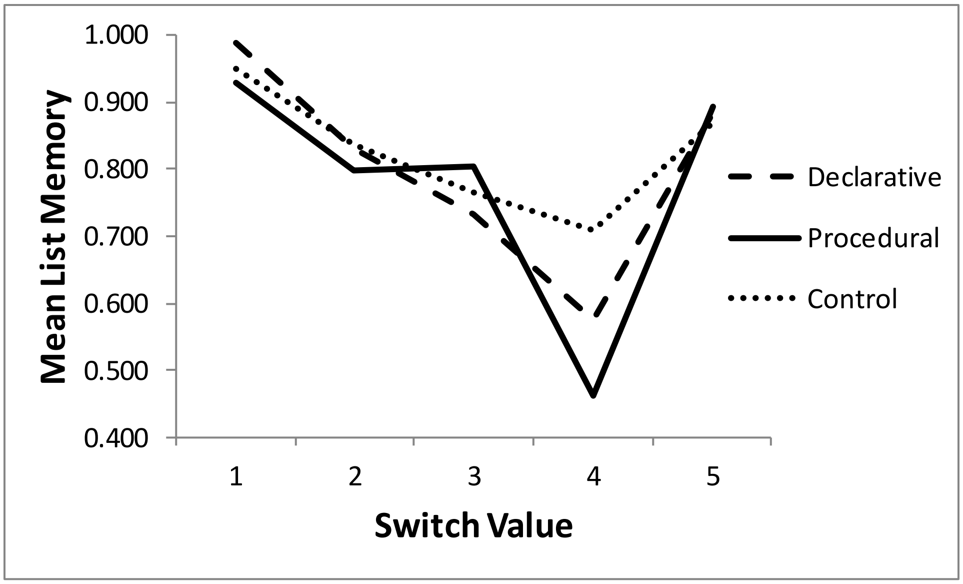

Figure 6. Mean percentage of lists remembered as a function of switch value for the task span in Experiment 2.

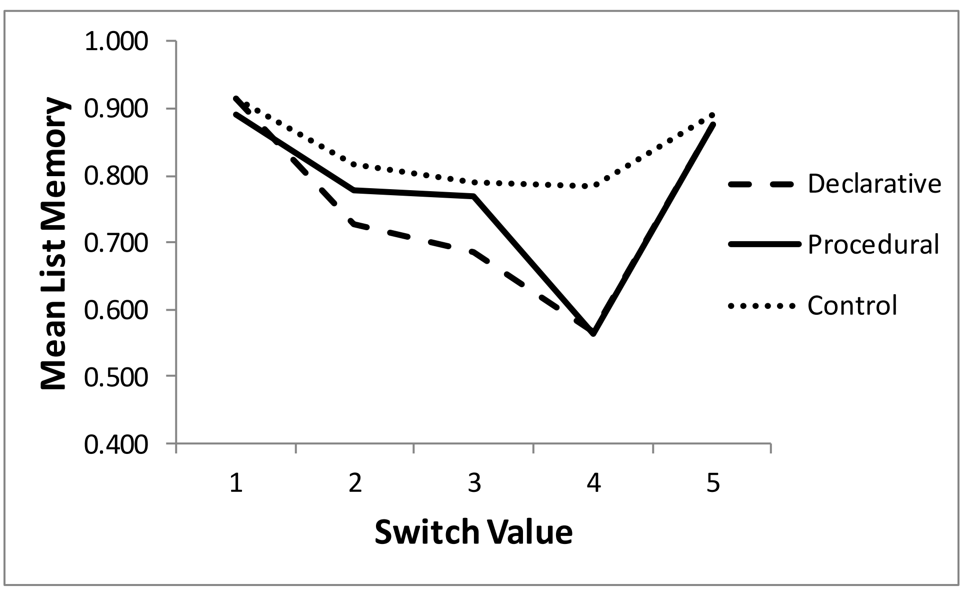

Figure 7. Mean percentage of lists remembered as a function of switch value for the memory span in Experiment 2.

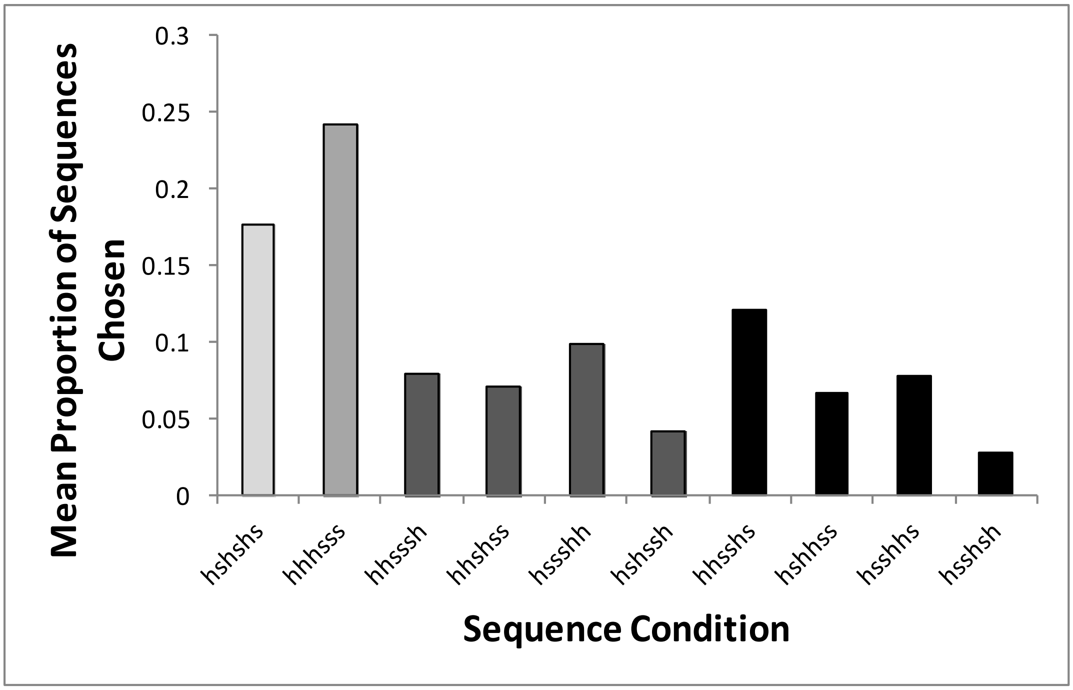

Figure 8a. The proportion of trials on which particular sequences were selected in the task span for Experiment 2.

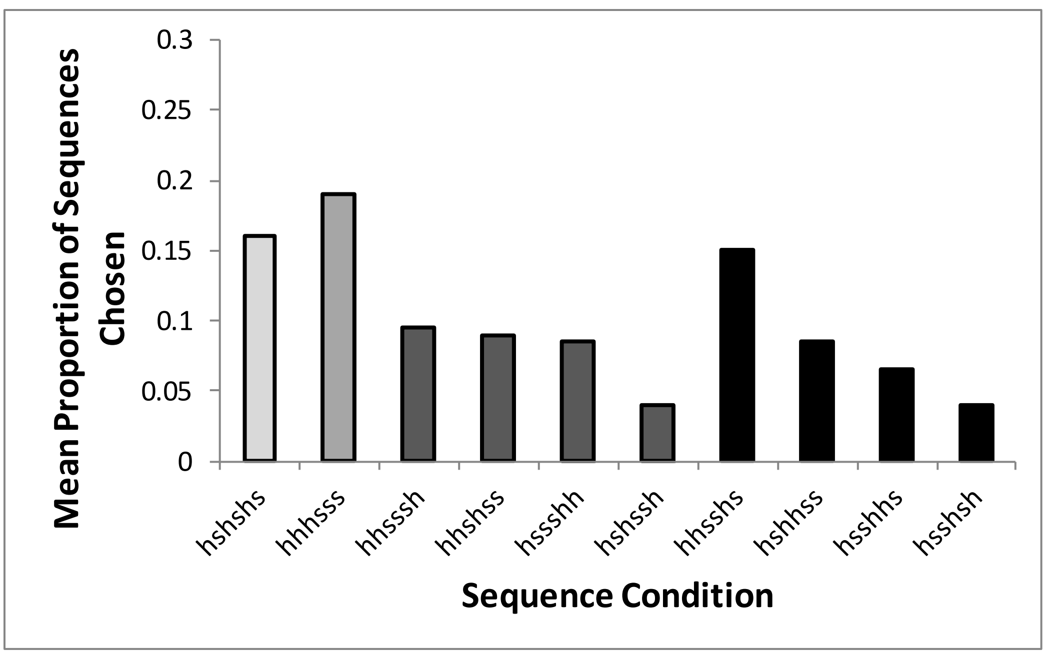

Figure 8b. The proportion of trials on which particular sequences were selected in the memory span for Experiment 2.

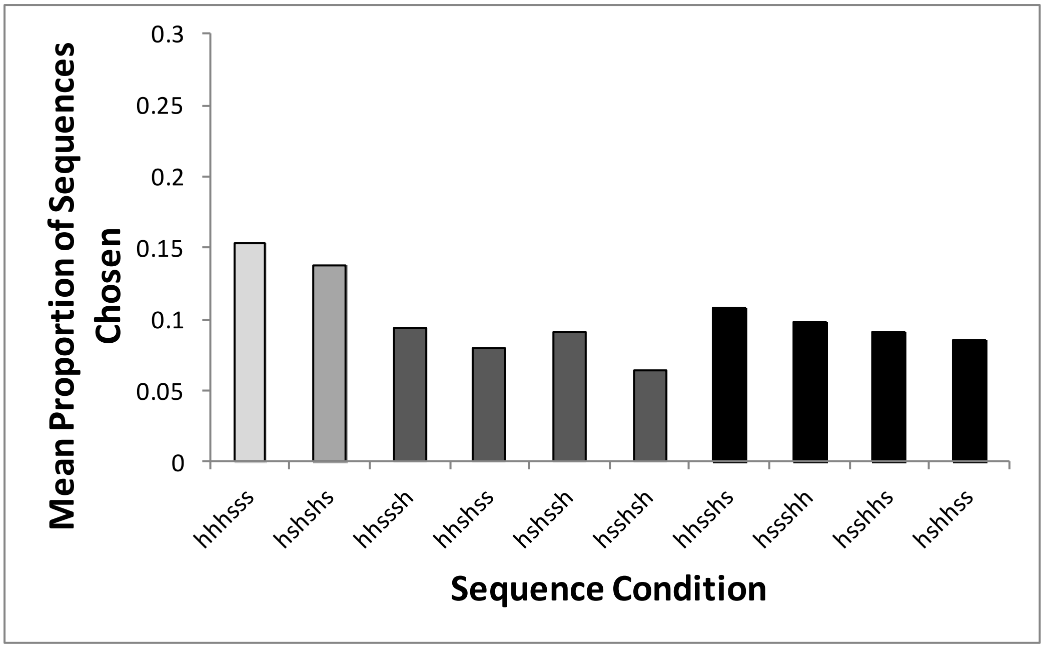

Figure 9a. The proportion of trials on which particular sequences were selected in the memory span for Experiment 3.

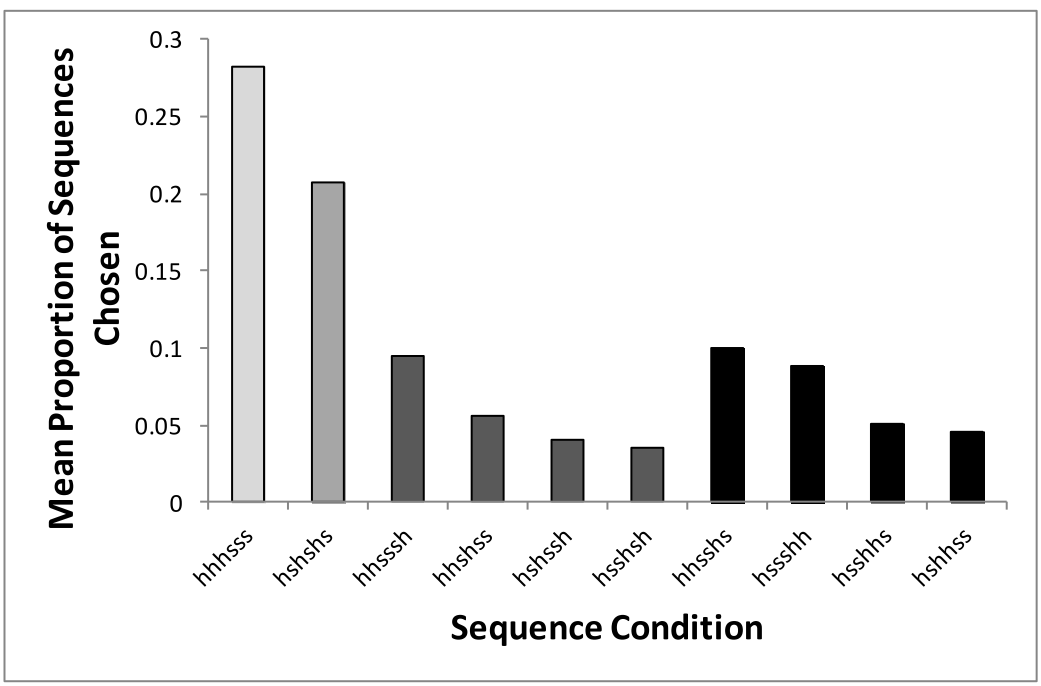

Figure 9b. The proportion of trials on which particular sequences were selected in the task span for Experiment 3.

Appendix A

Additional Data Analysis and Figures—Experiment 1

Prompt RT. Results of repeated measures ANOVAs suggest that local measures of serial position (6 levels) and task transition (2 levels) had significant impacts on generation response times for both the memory span and the task span. As is shown in Figure A1, the task span condition elicited longer response times for the first item generated in the list, with subsequent positions requiring less time for generation. In the memory span, the pattern was similar but positions following position one had faster generation response times than was seen in the task span. A 2 x 6 RM ANOVA with condition and serial position as within subjects factors indicated that there was a significant interaction between the span condition and position within the list, $F(5,490) = 39.66$, $p < .001$ on generation response times. Looking separately at task span and memory span, the main effect of serial position on prompt RT was significant for both conditions, task span, $F(5,410) = 505.10$, $p < .001$ and memory span, $F(5,405) = 338.37$, $p < .001$. The first position in a block elicited a much slower response time than all of the other subsequent positions, which might have driven the significant main effects. However, this was not the case. A significant main effect of serial position persisted even when the first position was eliminated, with earlier positions requiring longer generation periods than later positions for both the task span, $F(4,328) = 32.32$, $p < .001$, and the memory span $F(4,324) = 37.56$, $p < .001$.

Switching tasks, even at encoding, was costly for generation response times as indicated by significant RM ANOVAs. Reaction times to prompts were higher for trials on which the participants switched ($M = 513.55$, $SD = 145.31$) than when they repeated

(M = 430.51, SD = 100.03). There were significant main effects of transition on generation response times for the task span and the memory span, (Fs >69.08, ps < .001). These switch costs were not different between the two span tasks, as indicated by a non-significant interaction of condition and transition in a 2 x 2 RM ANOVA, $F(1,98)$ =2.166, p =.144.

Participants took longer to generate sequences that included more complexity than they did for simpler lists. A 2 x 4 repeated measures ANOVA with condition and complexity score as within subjects factors indicated a significant interaction of these factors on prompt response time, $F(3,288) = 2.65$, $p = .49$. There was less of an increase in response times as a function of complexity score in the memory span than in the task span, depicted in figure A2. There was also a significant interaction between condition and switch value as indicated by a 2 x 5 RM ANOVA examining these constructs, $F(4,324) = 23.23$, $p < .001$, which suggested a similar pattern of results as the complexity score and is illustrated in figure A3. Response times to prompts were significantly slowed by more complex lists in the memory span indicated by a significant main effect of this measure, $F(3,243) = 65.31$, $p < .001$ and the switch value, $F(4,308) = 46.54$, $p < .001$. The same pattern held true for the task span with complexity score, $F(3,246) = 46.30$, $p < .001$ and switch value, $F(4,288) = 45.52$, $p < .001$, significantly impacting generation time.

Target Response Times. Results of repeated measures ANOVAs suggest that local measures of serial position had a significant effect on target response times. As is shown in Figure A4, the task span condition elicited longer response times for the first target with subsequent positions requiring less time for task execution. In the memory span, the pattern was similar but positions following position one had faster response times than was seen in the task span. A 2 x 6 RM ANOVA indicated that there was a significant interaction between the span condition and position within the list on target response times, $F(5,490) = 28.526$, $p < .001$. There was also a significant main effect of serial position on target response times for both conditions, task span, $F(5,410) = 187.09$, $p < .001$, and memory span, $F(5,405) = 51.625$, $p < .001$. As with the generation response times, the first position in a block elicited a much slower response time than all of the other subsequent positions, which might have driven the significant main effects. This was again not the case. A significant main effect of serial position persisted even when this exceptionally long response was eliminated, with earlier positions requiring longer generation periods than later positions for both the task span, $F(4,328) = 25.12$, $p < .001$, and the memory span $F(4,324) = 9.48$, $p < .001$.

More complex sequences elicited longer response times than those that had fewer switches and/or a more defined structure whether participants were simply recalling the task names or actually carrying out the tasks. As shown in figure A5, in the task span there was a large drop in the response times for the lists with a complexity score of 8. This drop was not present in the memory span, which is responsible for a significant interaction between condition and complexity score, $F(3,288) = 104.55$, $p <.001$. Sequence complexity, $F(3,243) = 21.55$, $p < .001$, had significant effects on participants' response times to the targets in the memory span. The same pattern held for the task span, with and complexity, $F(3,246) = 109.74$, $p < .001$, significantly impacting target response times.

Task Memory. Memory for tasks was best for positions early in the lists. The task span showed a larger difference in memory for tasks between the first position compared to subsequent positions than in the memory span, depicted in figure A6. Results of a 2 x 6 repeated measures ANOVA indicated that there is a significant interaction between span condition and list position, $F(5,370) = 4.13$, p -.001. List position had a significant impact on memory for tasks in the task span, F (5,405) = 47.84, $p < .001$, and in the memory span $F(5,370) = 26.064$.

Memory did not differ between repetitions and switch trials in the memory span (repetitions: $M = .92$, $SD = .245$, switches: $M = .922$, $SD = .281$), but it was lower for switch trials in the task span (repetitions: $M = .946$, $SD = .289$, switches: $M = .926$, $SD = .279$). This difference in transition effects is seen in the results of a significant interaction between span type and transition, $F(1,74) = 13.245$, $p = .001$. Transition had a significant effect on memory in the task span, $F(1,81) = 67.94$, $p < .001$, but not the memory span, $F(1,74) = .330$, $p = .567$.

The number of switches in the list had a significant impact on how individuals were able to remember the tasks, such that lists with more switches had lower task memory (except for the 5 switch condition). There was no difference in the way the number of switches affected task memory in the task span compared to the memory span, indicated by the non-significant interaction of these two factors on task memory, $F(4,248) = .686$, $p = .602$. But looking at the two conditions individually we see that the switch value had significant effects on memory in both the memory and task spans, (*Fs* >12.742, *p*s < .001. These effects are depicted in figure A7.

The effects of complexity score on task memory showed a similar pattern of results (figure A8). Lists with higher complexity resulted in lower task memory. There was no difference between this effect in the task span and the memory span, $F(3, 222) = .052$, $p = .984$. The impact of this variable on task memory was significant for both the task span $F(3, 243) = 32.085$, $p < .001$, and the memory span $F(3, 222) = 19.66$, $p < .001$.

List Memory. List memory was analyzed as a function of the global measure of complexity score using repeated measures ANOVAs to investigate differences across this variable. Complexity had a similar effect on list memory between the task span and the memory span which was supported by the results of a 2 x4 repeated measures ANOVA investigating the effects of sequence complexity on list memory. There was no significant interaction between the two conditions, $F(3,288) = 1.895$, $p = .130$. The complexity score, $F(3,243) = 22.82$, $p < .001$ had significant main effects on participants overall memory for sequences in the memory span. Additionally, the complexity score, $F(3,246) = 31.87$, $p < .001$ had a similar effect of decreasing memory for more complex lists in the task span. Complexity score data are illustrated in figure A9.

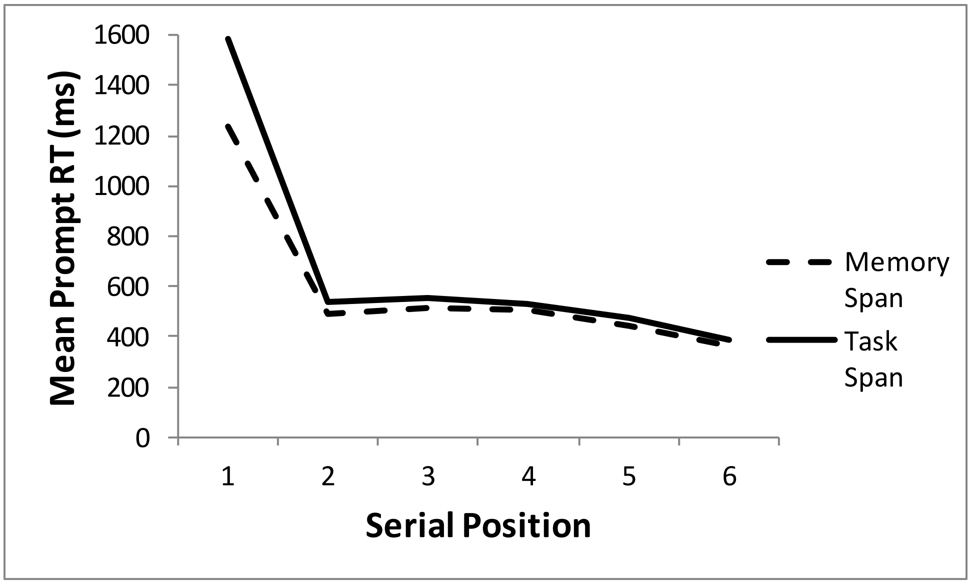

Figure A1. Mean response times to prompts when generating sequences as a function of serial position for the memory span and task span in Experiment 1.

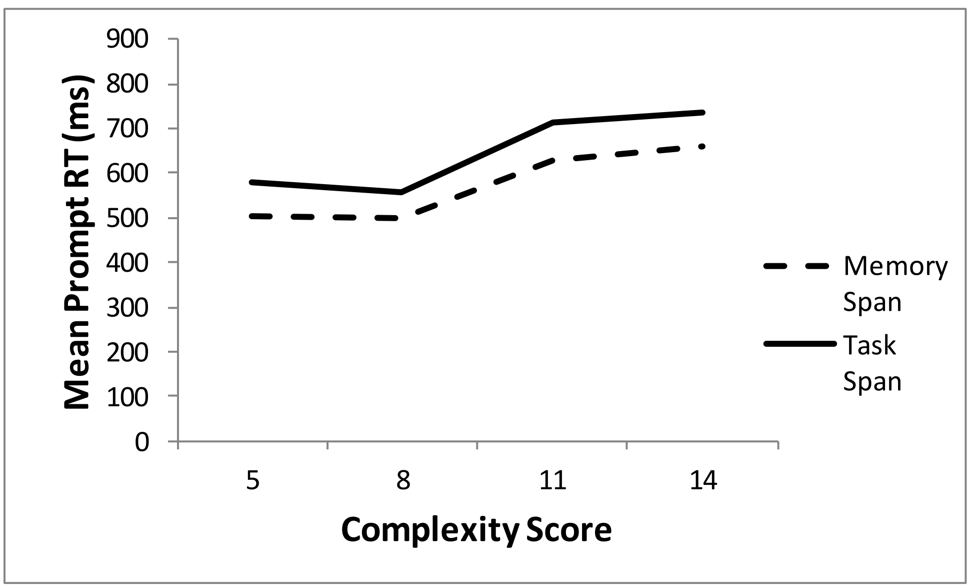

Figure A2. Mean response times to prompts when generating sequences as a function of the complexity score for the memory span and the task span in Experiment 1.

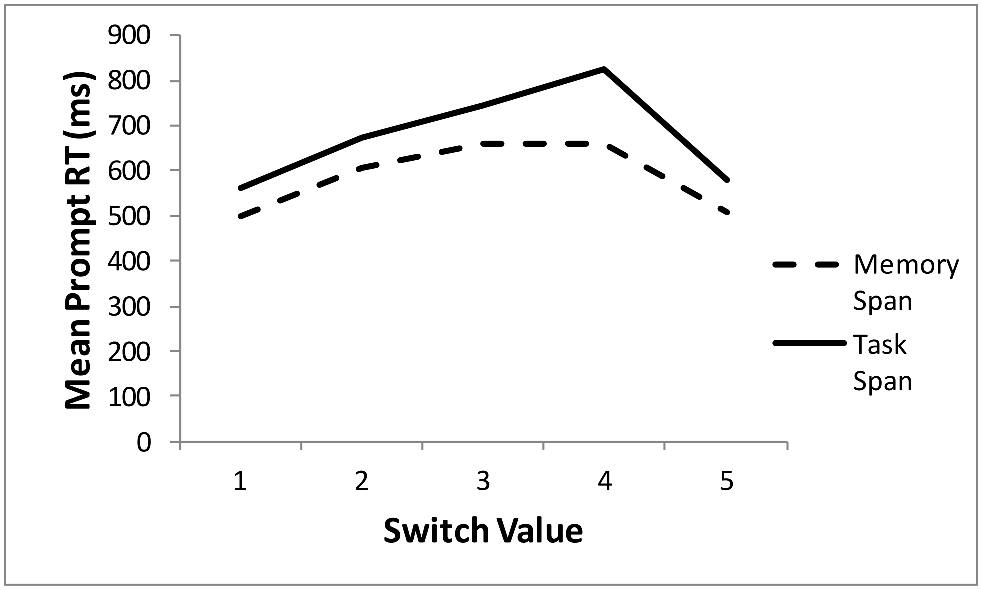

Figure A3. Mean response times to prompts when generating sequences as a function of the switch value for the memory span and the task span in Experiment 1.

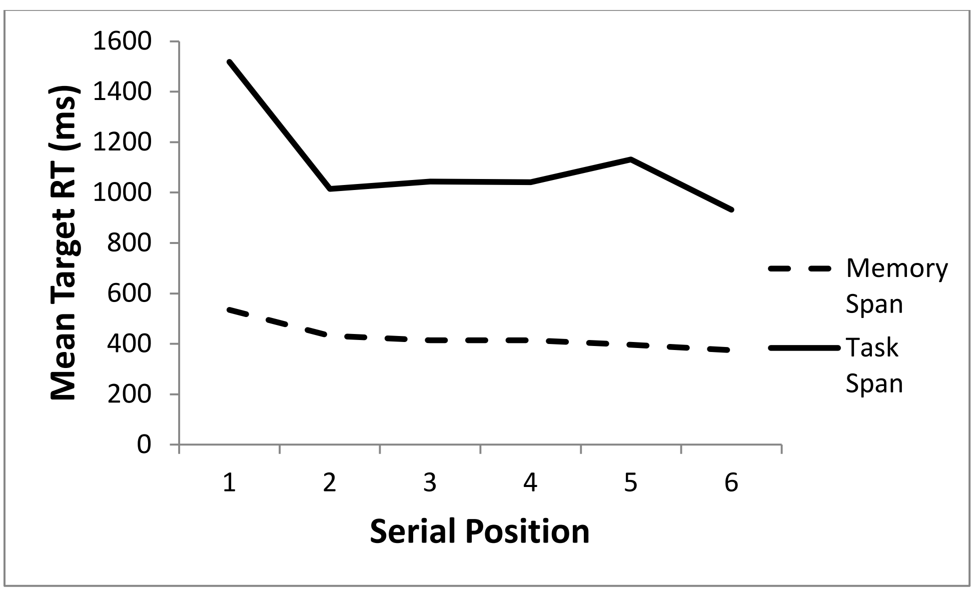

Figure A4. Mean response times to targets as a function of serial position in Experiment 1.

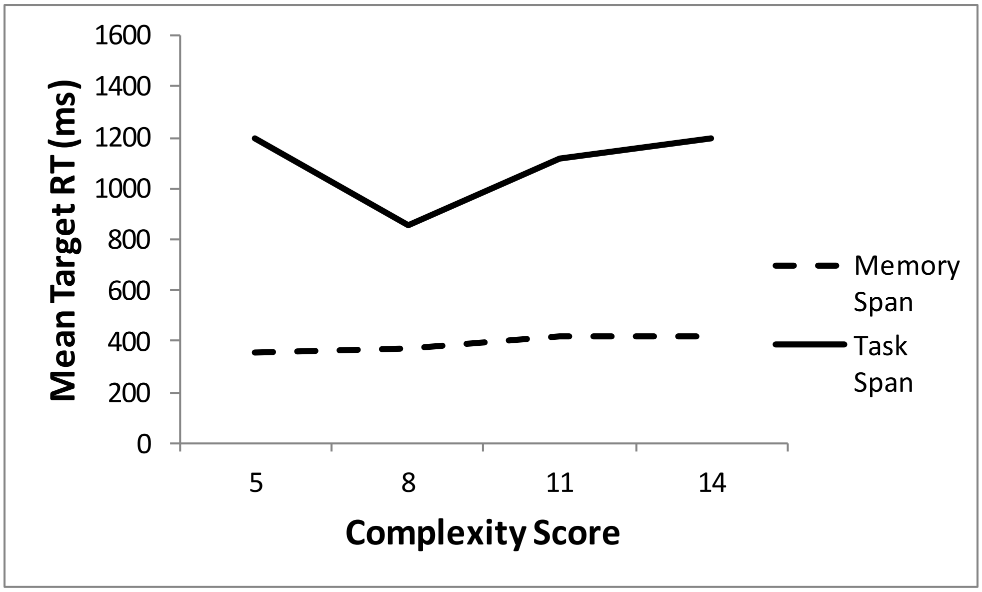

Figure A5. Mean response times to targets as a function of complexity score in Experiment 1.

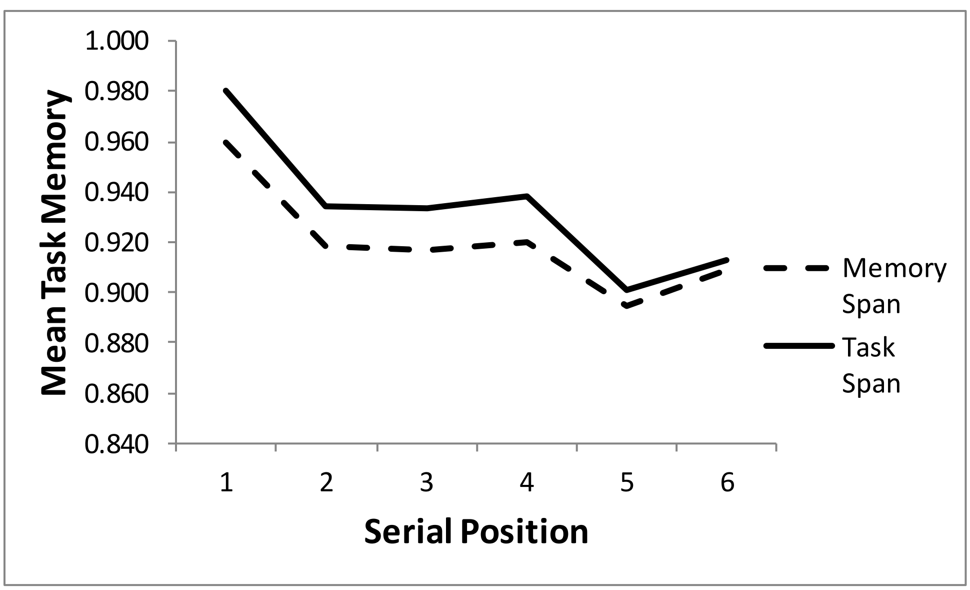

Figure A6. Mean percentage of tasks accurately remembered in the task span and memory span as a function of serial position in Experiment 1.

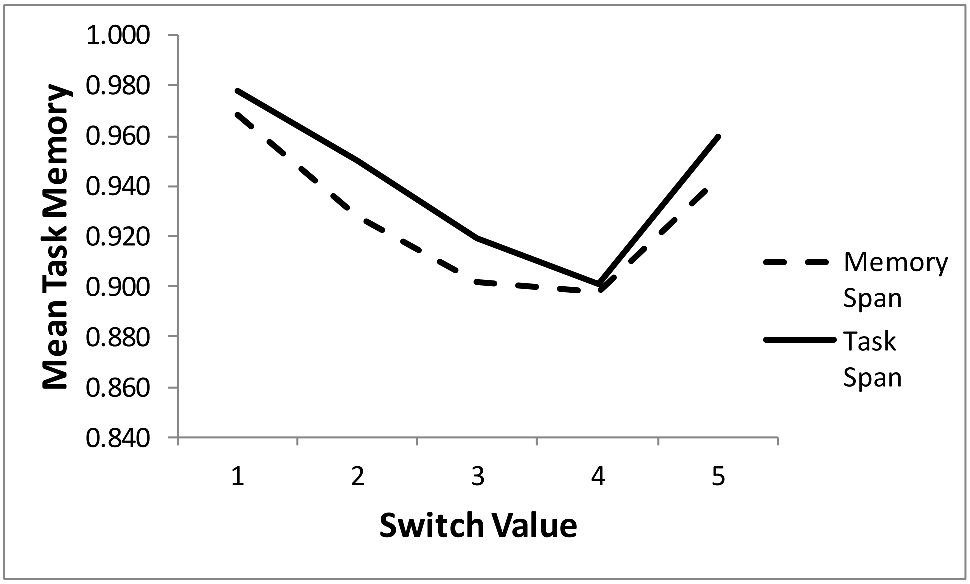

Figure A7. Mean percentage of tasks accurately remembered in the task span and memory span as a function of switch value in Experiment 1.

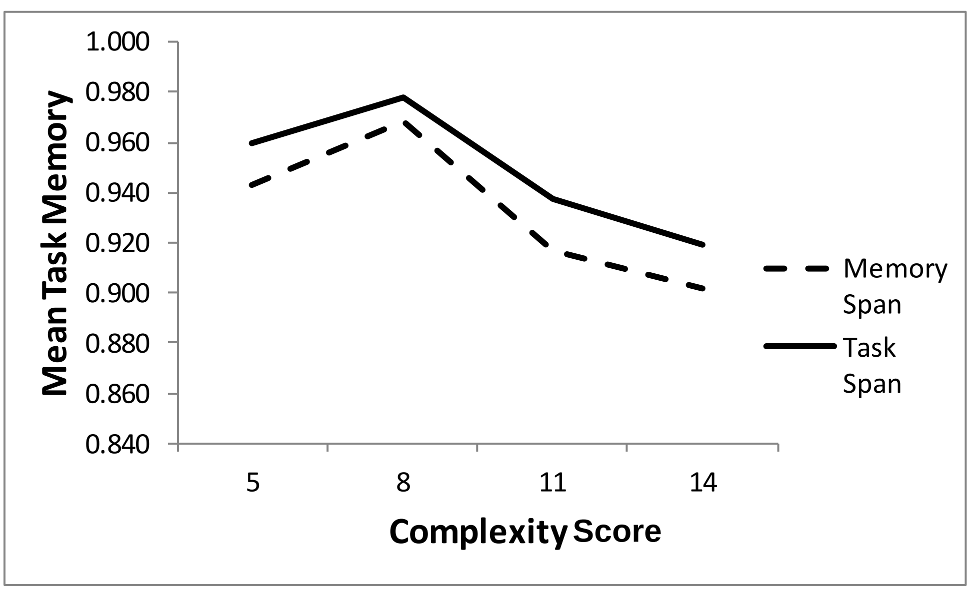

Figure A8. Mean percentage of tasks accurately remembered in the task span and memory span as a function of complexity score in Experiment 1.

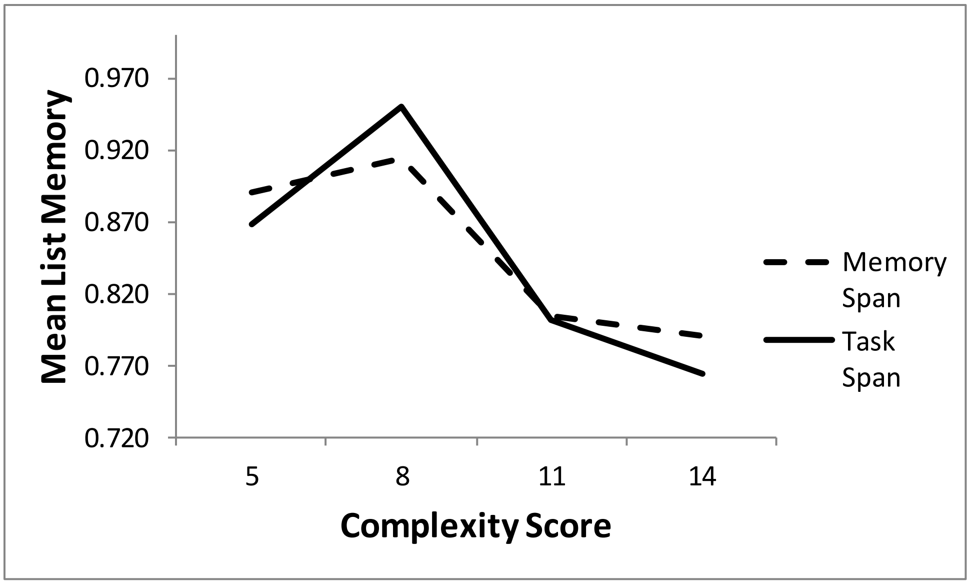

Figure A9. Mean percentage of lists accurately remembered in the task span and memory span as a function of complexity score in Experiment 1.

Appendix B

Additional Data Analysis and Figures—Experiment 2

Prompt Response Times. The working memory manipulation did not have any impact on the time it took participants to generate sequences. This was true when analyzed as a function of all independent variables. Results of four repeated measures ANOVAs suggested that there were no differences in the effect of serial position, task transition, switch value, or complexity score, (all Fs < 1.822, ps > .181) on generation times between participants who received the working memory manipulation and those who did not. There were also no significant three-way interactions of any of these variables with the span condition and experimental condition.

Target Response Times. The working memory load did impact the time it took participants to respond to targets, when analyzed as a function of the position in a list. There was a significant interaction between experimental condition and position, $F(5,425) = 2.266$, $p = .047$ in regards to target response times (figures B1 and B2). After participants made their response to position one, there was a steeper decrease in response times in the load condition than in the no-load condition.

Task Memory. Task memory was not influenced differently between conditions when analyzed as a function of serial position and task transition, suggested by the lack of a significant interaction between serial position, $F(5,425) = 1.529$, $p = .179$, or task transition, $F(1,85) = .000$, $p = .998$, and experimental condition on memory for tasks. There were significant interactions between the switch value, $F(4, 280) = 7.818$, $p < .001$, and the complexity score, $F(3, 252) = 3.057$, $p = .029$, and memory for tasks between those who received the working memory manipulation and those who did not. As the complexity of sequences increased, participants' memory for tasks decreased more in the load condition than in the no-load condition, depicted in figures B3-B6.

List Memory. There was a significant interaction between complexity score $F(3, 252) = 3.194$, $p = .024$, with experimental condition on memory for lists. Lists with greater complexity had lower memory in the load condition than in the no-load condition, seen in figures 9-12. List memory was also significantly impacted by complexity score for the task span, $F(3,285) = 33.596$, $p < .001$, and memory span, $F(3,252) = 18.965$, $p < .001$, separately. Higher complexity scores resulted in lower memory for lists in all conditions. See figures B7 and B8.

Declarative and procedural component analysis.

Prompt Response Times. Participants' responses to prompts showed no differences between the declarative and procedural working memory manipulations. The response to prompts was not different between the two manipulations, as demonstrated by repeated measures ANOVAs, all *F*s < .839, *p*s > .511. This was true when analyzed as a function of serial position, transition, switch value, and complexity score.

Task Memory. There were no significant differences in the way participants remembered tasks between the two manipulations. Task memory did not vary differently between the declarative and procedural working memory manipulations as a function of the position in the list, task transition, sequence switch value or complexity score. This was indicated by non-significant interactions, all *F*s < .470, all *p*s > .798.

List Memory. There was no significant difference in the effect of complexity score on participants memory for lists, $F(3,57) = 1.072$, $p = .368$.

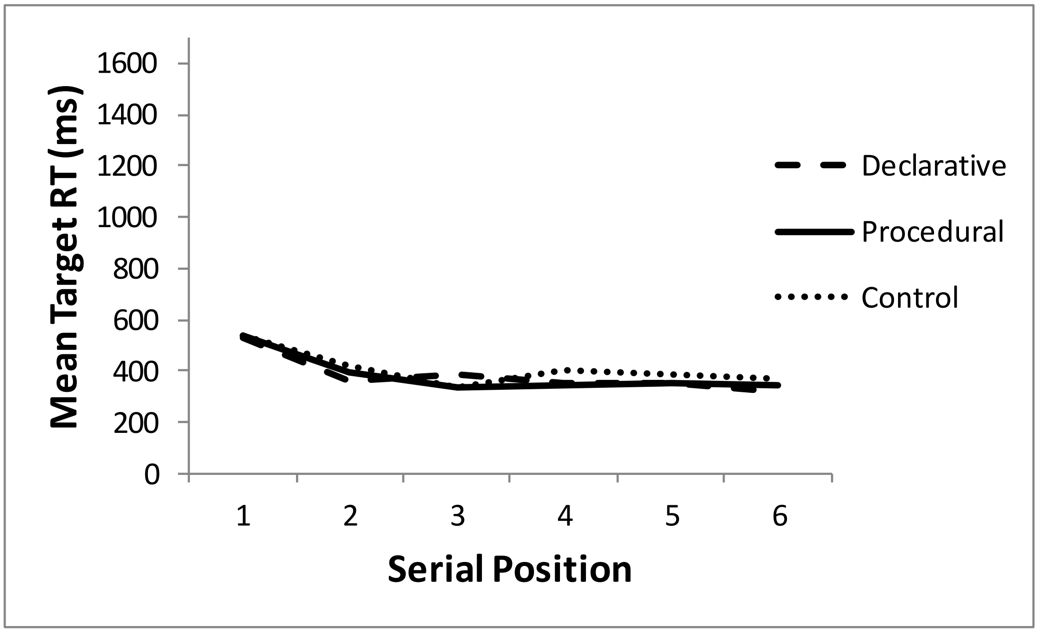

Figure B1. Mean response times to targets when generating sequences as a function of serial position for the memory span in Experiment 2.

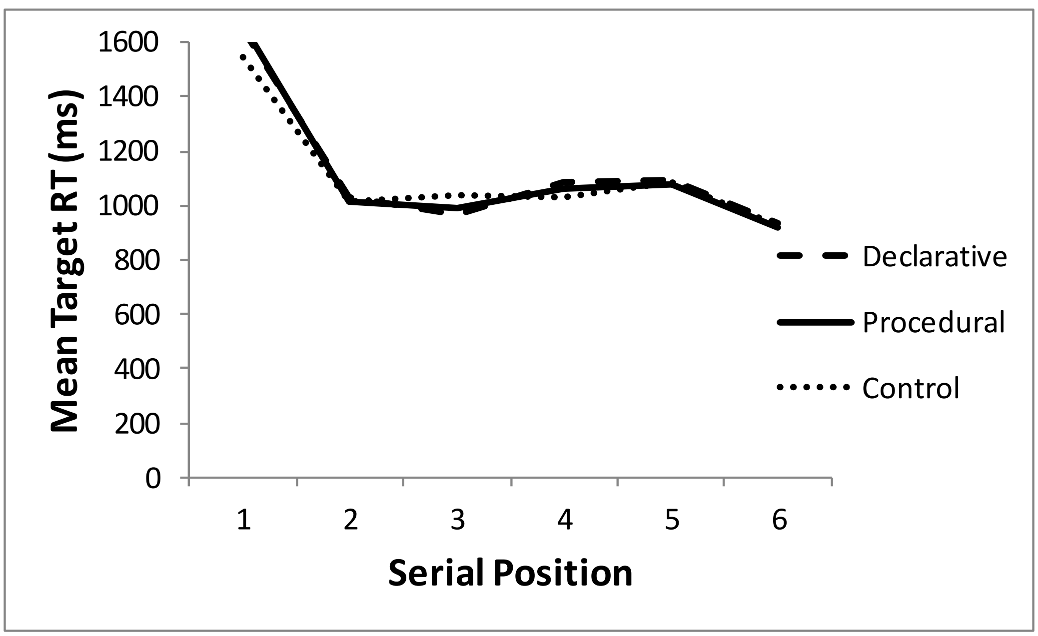

Figure B2. Mean response times to targets when generating sequences as a function of serial position for the task span in Experiment 2.

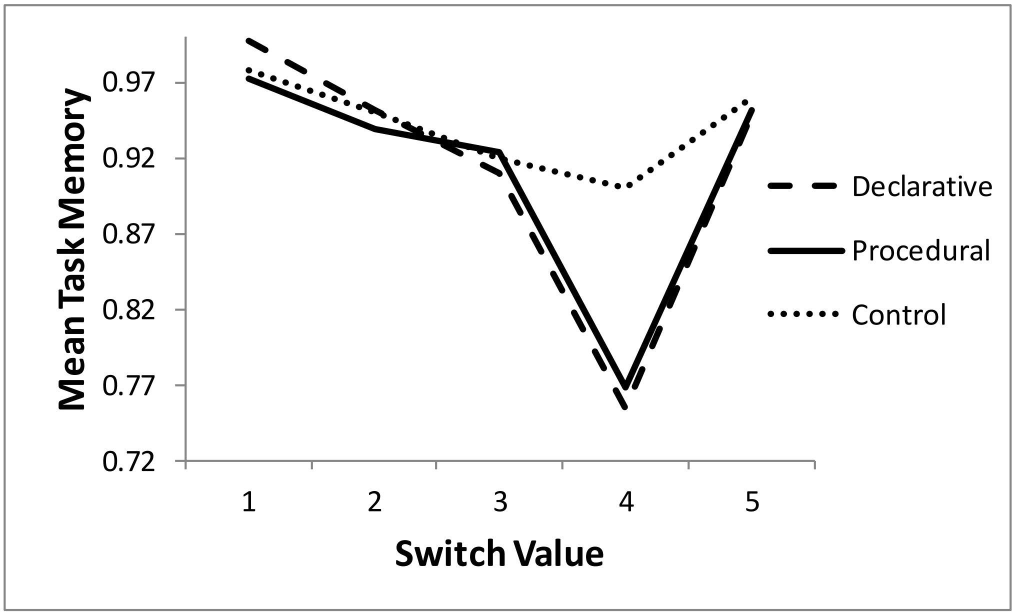

Figure B3. Mean percentage of tasks remembered as a function of switch value for the task span in Experiment 2.

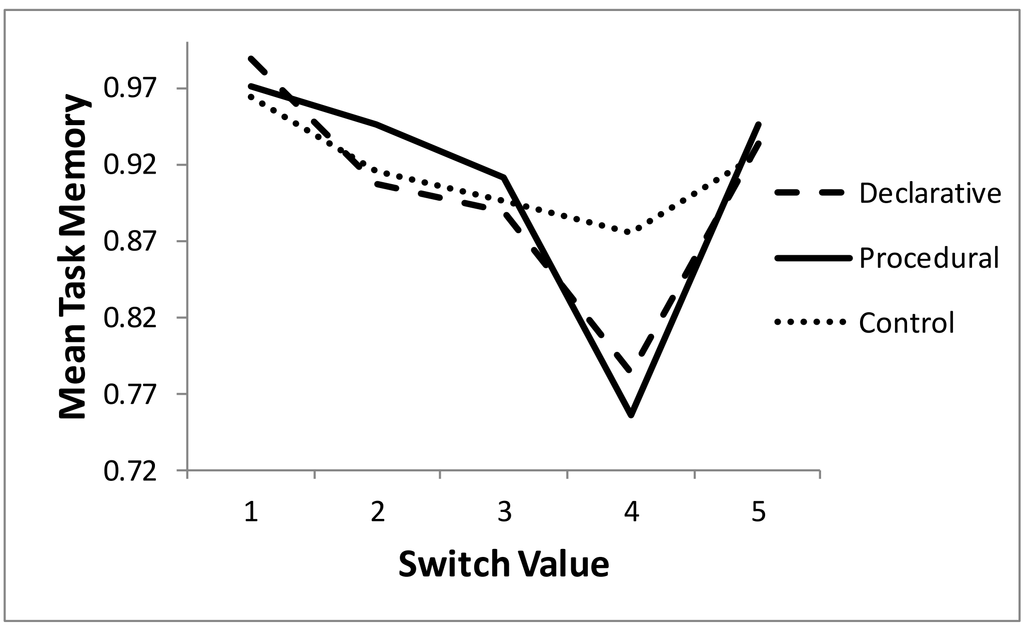

Figure B4. Mean percentage of tasks remembered as a function of switch value for the memory span in Experiment 2.

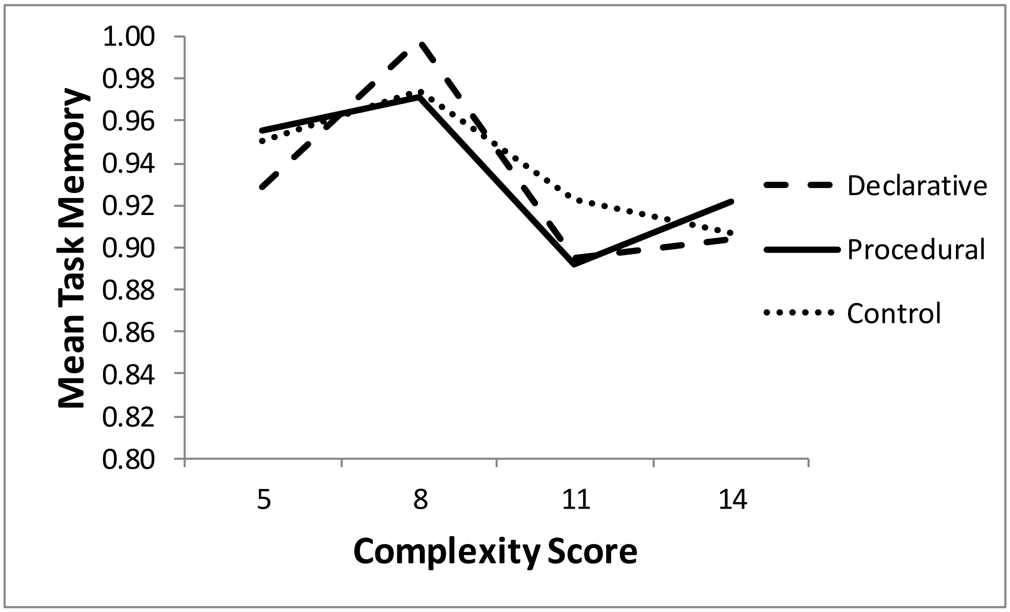

Figure B5. Mean percentage of tasks remembered as a function of complexity score for the task span in Experiment 2.

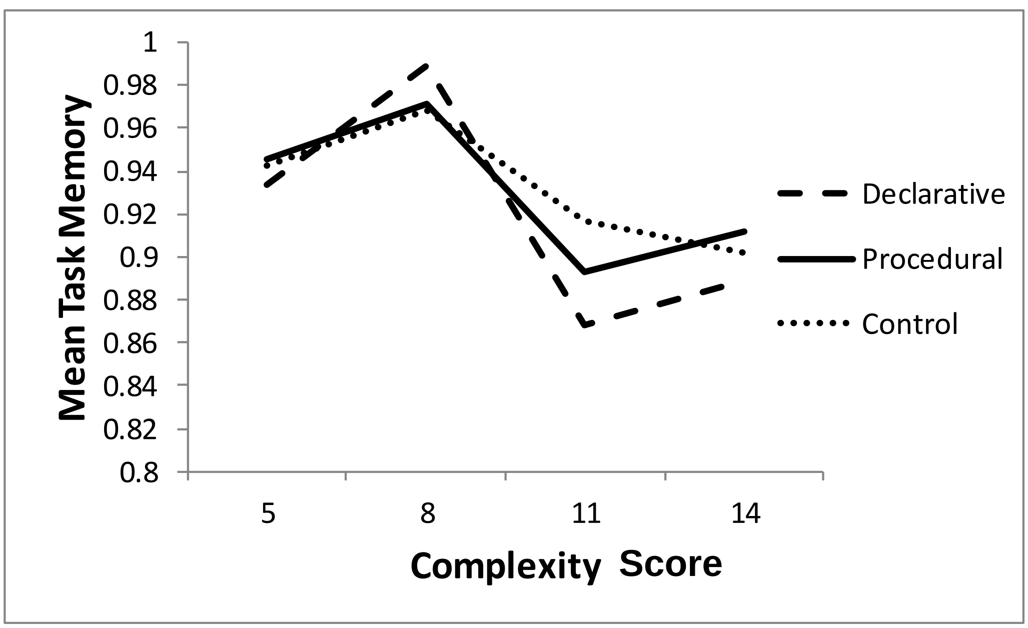

Figure B6. Mean percentage of tasks remembered as a function of complexity score for the memory span in Experiment 2.

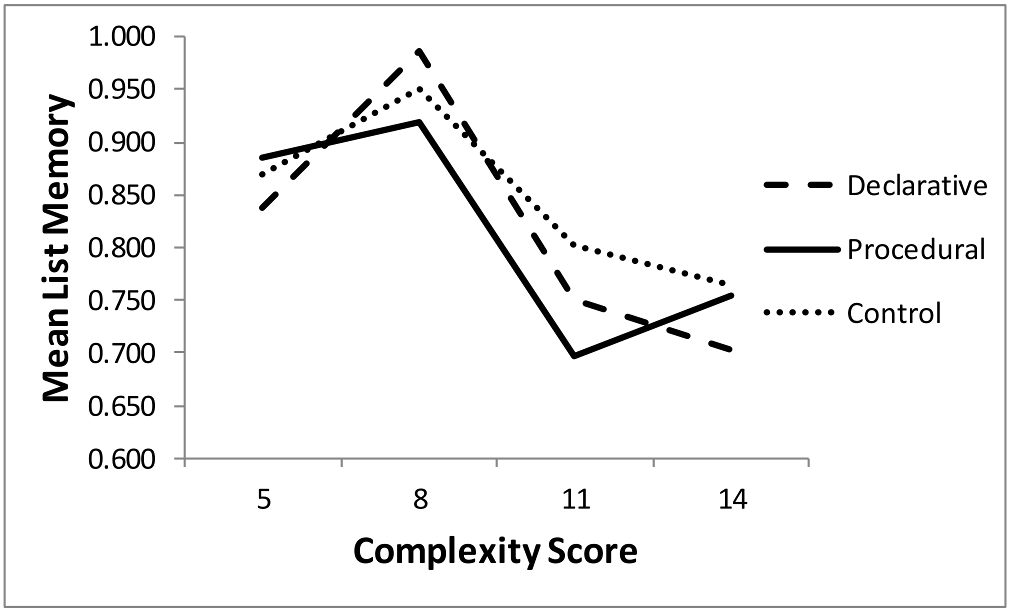

Figure B7. Mean percentage of lists remembered as a function of complexity score for the task span in Experiment 2.

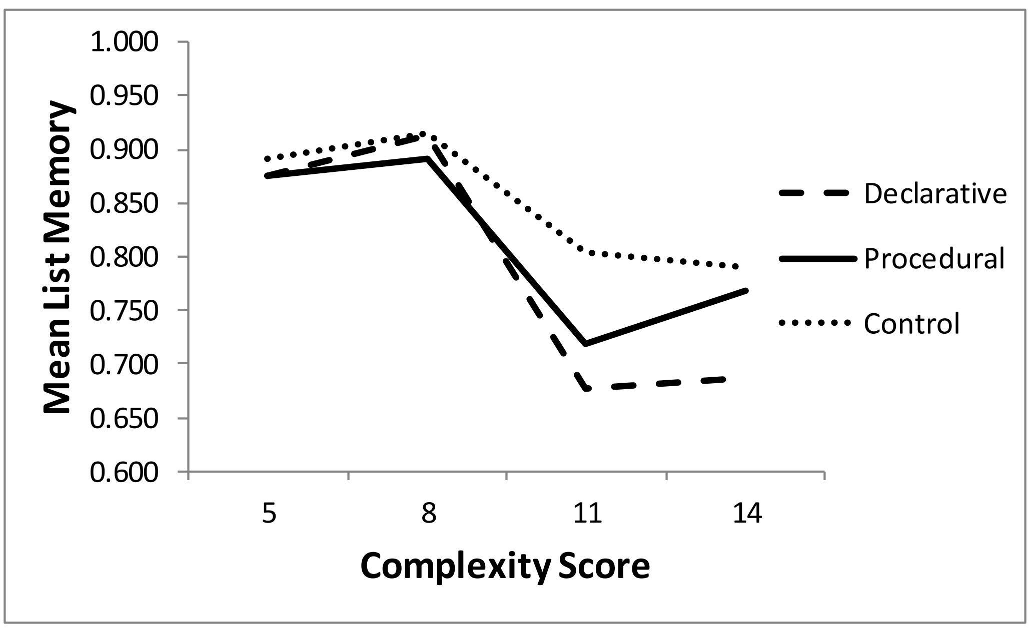

Figure B8. Mean percentage of lists remembered as a function of complexity score for the memory span in Experiment 2.

Appendix C

Additional Data Analysis and Figures—Experiment 3

Prompt Response Times. There were no overall differences between the time participants took to generate sequences in the two conditions, but we did observe some differences when accounting for different sequence characteristics. Participants' generation response times were faster at every position in a sequence for both the memory span and the task span when they were subjected to the executive control manipulation compared to when they were not. Switch costs between different trial types were smaller in the memory span and in the task span for the experimental condition when compared to the control condition. There was no difference between conditions in generation response times between lists that had greater complexity or higher switch values.

Results of four repeated measures ANOVAs supported these findings. There was a significant interaction between serial position and experimental condition, $F(5, 425) = 3.97$, $p = .002$, on generation response times, with longer generation times in the single-task condition (figures C1 and C2). Response times for the first serial position in each condition were the longest out of all positions. The drop in response times after position one was much greater in the single-task condition than in the dual-task condition. Task transition also showed a significant interaction with experimental condition, $F(1, 85) = 5.205$, $p = .025$; switch and repetition trials were faster in the single-task condition, and the overall difference between the two types of trials was also smaller. Neither switch value , $F(4, 280) = 0.508$, $p = .730$, or complexity score, $F(3,252) = 0.210$, $p = .889$, interacted with experimental condition—there was no difference in the generation times between experiments as a function of these variables. There were also no significant three-way interactions of any of these variables and the span condition and experimental condition.

Target Response Times. In general, target response times were faster in the executive control manipulation condition than in the control condition. This was evident when this dependent measure was examined as a function of the local measure of serial position. Responses to targets were faster as a function of serial position for the dual-task condition than the control condition. There was a significant interaction between experimental condition and position, $F(5,425) = 2.392$, $p = .037$, in regards to target response times (figures 15 and 16). Participants sped up more as the block of 6 trials progressed in the dual-task condition compared to the control condition.

There was no significant interaction between complexity score, $F(3, 252) = 1.185$, $p = .316$, and experimental condition on target response times.

Task Memory. Task memory was not significantly different between the two experimental conditions. Across all independent variables there were no differences in the level of memory for tasks between the dual-task condition and the single-task condition. There were no significant interactions between serial position, transition, switch value, or complexity score and manipulation on memory for tasks, all Fs < 1.152, ps > .332.

List Memory. List memory was not affected by the manipulation of executive control in this experiment. Based on the results of a RM ANOVA, we concluded that there was no significant interaction of complexity score, $F(3, 252) = .733$, $p = .533$, and experimental condition on memory for lists.

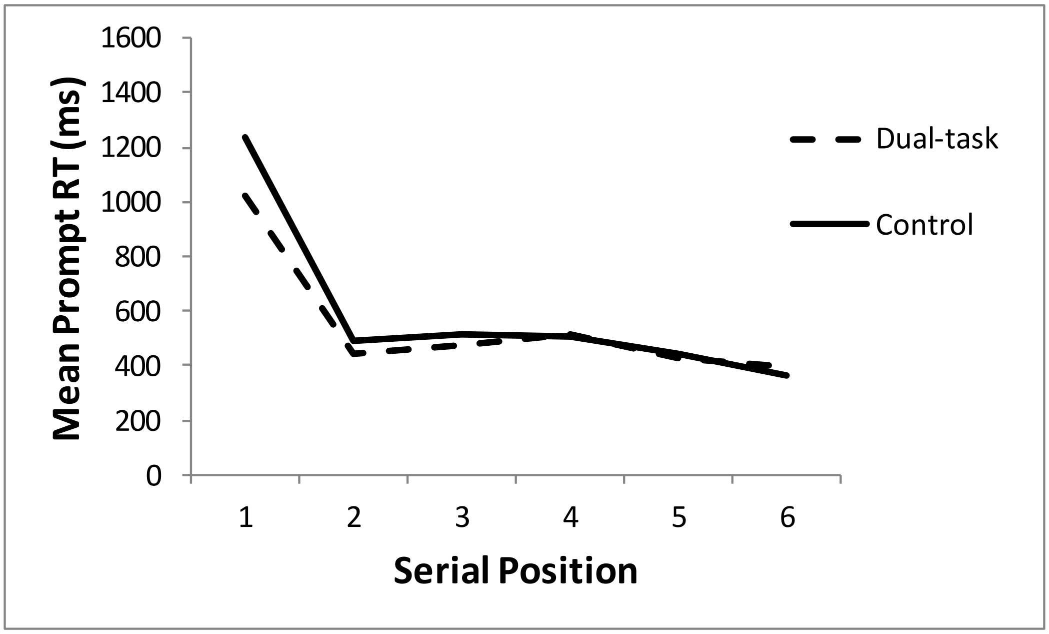

Figure C1. Mean response times to prompts when generating sequences as a function of serial position for the memory span in Experiment 3.

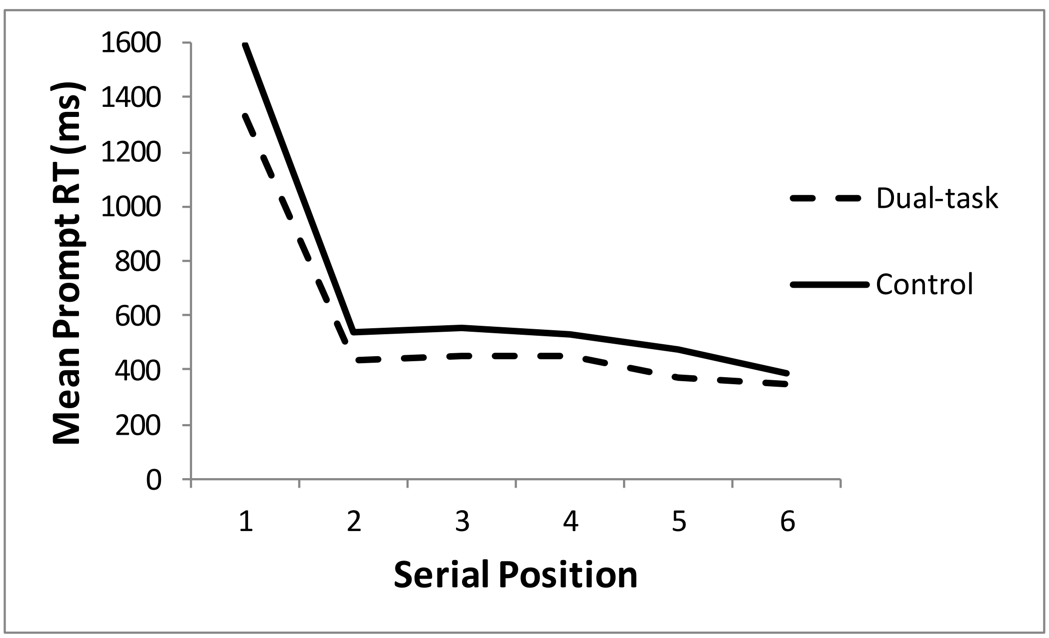

Figure C2. Mean response times to prompts when generating sequences as a function of serial position for the task span in Experiment 3.

Curriculum Vitae

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EDUCATION:

M.S., Cognitive Psychology, **Lehigh University**, Bethlehem, Pennsylvania — Expected 2012

B.A., Psychology, **The College of New Jersey**, Ewing, New Jersey — May 2010

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Instructor: Dominic Packer, Ph.D.
3 Part guest lecture series, Memory

Teaching Assistant — Lehigh University PSY 176, Mind and Brain
Instructor: Kate Arrington, Ph.D.
Guest lecture, Neuropsychology of Memory—*Spring 2011*
Co-instructor for weekly laboratory session—*Spring 2012*

Teaching Assistant — Lehigh University PSY 110, Statistical Analysis of Behavioral Data
Instructor: Almut Hupbach, Ph.D.
Instructor for weekly laboratory session

PRESENTATIONS

Reiman, K.M., Weaver, S. M., & Arrington, C. M. (2011, March). The effect of complexity on implementing a plan in the task span paradigm. Poster presented at the annual meeting of the Eastern Psychological Association, Cambridge, MA.

Reiman, K.M., Weaver, S.M., & Arrington, C.M. (2011, November). Encoding and choice in the task span procedure. Poster presented at the annual meeting of The Psychonomic Society, Seattle, WA.

Weaver, S.M., **Reiman, K.M.,** & Arrington, C.M. (2011, November). Predictable stimulus positions decrease bottom-up influences on task choice. Poster presented at the annual meeting of The Psychonomic Society, Seattle, WA.

Reiman, K.M., Arrington, C.M. (2012, March). Encoding and retrieval in the task span procedure. Oral presentation at the annual meeting of the Eastern Psychological Association, Pittsburgh, PA.

COMPLETED PROJECTS

Lehigh—Master's Thesis — April 2012
Executive Control, Working Memory and Action Planning: An Individual Differences Approach

Lehigh—First Year Project — June 2011
Encoding and Choice in the Task Span Procedure

TCNJ—Honor's Thesis — May 2010
Aging and Isolation Effects, a Study of Real World Actions
Under the direction of Tamra J. Bireta

PROJECTS IN PROGRESS

Reiman, K.M., Arrington, C.M., & Weaver, S.M. (n.d). Encoding and choice in the task span procedure. Manuscript in progress.

HONORS

2010	Degree with honors	The College of New Jersey
2010	Psychology Department Honors	The College of New Jersey
2007-2010	Dean's List	The College of New Jersey
2006-2007	Dean's List	Lafayette College

UNDERGRADUATE RESEARCH EXPERIENCE:

MEMORY & AGING LAB *(lab manager Spring 2010)* **January, 2009-May 2010**

Responsibilities Included:

- data Collection
- participant Recruitment
- presentations to local community regarding memory changes in older adults
- research design
- ethics training
- training of new lab members
- organization of RA schedules
- ensuring RA engagement

PREJUDICE & DEVELOPMENT LAB **January-May, 2009**

Responsibilities Included:

- data collection and analysis
- review of academic literature
- ethics training

REACH LAB **January-May 2008**

Responsibilities Included:

- database management
- review and presentation of academic literature
- ethics training
- observation of qualitative data collection

PROFESSIONAL SERVICE

Ad Hoc Reviewer, *Psychological Science* **October, 2011**

Lehigh University Graduate Student Senate **January 2011-present**

Unit representative

LVAIC Undergraduate Psychology Conference **April 16, 2011**

Judge

PROFESSIONAL AFFILIATIONS

Association for Psychological Science

Eastern Psychological Association

Student Member

Women in Cognitive Science

Psi Chi, Psychology Honor Society

COMMUNITY SERVICE

Girl Scouts USA troops 8225, 8747 **December 2010-present**
Leader

Alpha Phi Omega **January 2009- May 2010**
Member