This dissertation titled
Attentional Mechanisms in Children’s Complex Memory Span Performance

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ABSTRACT

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Working memory is a system devoted to the maintenance of information in the service of complex cognitive processing and is conventionally measured using complex memory span tasks. Developmental memory research has examined how mechanisms such as short-term memory storage, processing efficiency, retention duration, and focus of attention (i.e., limited attentional resources for activating contents of working memory) constrain complex memory span. There continues to be a need, however, for the examination of specific attention control mechanisms in children’s complex memory span performance.

This dissertation examined the role of two attention control mechanisms; sustained attentional focus and attentional focus switching, in typically developing 7- to 11-year-old children’s complex memory span performance. Sustained attentional focus was explored because of suggestions in the literature implicating its importance to higher-order cognitive functioning. Sustained attentional focus may be critical to complex memory span performance because there is a need to maintain general vigilance over multiple steps in a complex memory span task. Attentional focus switching was assessed because emerging data in the adult literature suggest that it predicts performance on complex memory span. It appears that individuals rapidly switch their focus of attention
between storage and processing while performing complex memory span tasks. Efficient attention switching thus improves complex memory span.

Children’s sustained attentional focus was indexed by their ability to maintain attention over time on the standardized vigilance measures from the *Gordon Diagnostic System*. Using experimental measures, attentional focus switching was indexed by the accuracy and speed to switch the focus of attention between two different simple stimuli. Two measures were used for each of the predictor constructs (sustained attentional focus, attentional focus switching) and the dependent variable (complex memory span). General Linear Modeling procedures revealed that, when controlling for age effects, only attentional focus switching accuracy emerged as the significant predictor of children’s complex memory span in the present study. Results are in strong agreement with the adult literature implying the critical role of attentional focus switching in working memory. The present study is the first to explicitly examine the contribution of attentional focus switching to children’s complex memory span. Additionally, these results substantiate data that further elaborate aspects of domain-general executive attention in developmental working memory models.

Approved: _____________________________________________________________

James W. Montgomery

Professor of Hearing, Speech and Language Sciences
DEDICATION

To my mentor Dr. Jim Montgomery
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CHAPTER 1: INTRODUCTION

It is well established that children’s working memory abilities are important to developmental improvements in a variety of higher-level cognitive abilities, including general intellectual functioning, language skills, and school achievement (Adams & Hitch, 1997; Bayliss, Jarrold, Gunn, & Baddeley, 2003; Daneman & Merikle, 1996; Gathercole, 1999; Lepine, Barrouillet, & Camos, 2005; Montgomery & Evans, 2009; Montgomery, Magimairaj, & O’Malley, 2008). Working memory, a limited capacity system, is essential to encoding, storage and retrieval of information being processed in any of a range of cognitive tasks (Atkinson & Shiffrin, 1971; Baddeley, 2003; Cowan, 1995; Engle, Kane, & Tuholski, 1999; Just & Carpenter, 1992; Miller, Gallanter, & Pribram, 1960). It has been conventionally measured using complex memory span tasks that are characterized by maintenance of items in storage in the face of processing (e.g., Case, 1985; Daneman & Carpenter, 1980). Developmental memory research indicates that working memory comprises the separable yet interactive components of short-term memory storage and processing speed (Bayliss et al., 2003; Bayliss, Jarrold, Baddeley, Gunn, & Leigh, 2005). Despite considerable research characterizing these two components/mechanisms, researchers have recently begun to examine the extent to which these mechanisms individually and collectively influence complex memory span (Bayliss et al., 2003, 2005). Bayliss et al. (2005) evaluated two sources of working memory constraints (storage and processing efficiency) and found that both domain specific storage and general processing efficiency contributed to a significant amount of variance in complex memory span performance.
While researchers believe that attentional capacity is also a source of variation in complex memory span performance, developmental research in this regard is sparse (e.g., Barrouillet & Camos, 2001; Barrouillet, Gavens, Vergauwe, Gaillard, & Camos, 2009; Cowan et al., 2005). Additionally, different research groups do not conceptualize the role of attention in complex memory span performance in the same way. For example, some theorists equate attentional capacity and working memory capacity (Cowan et al., 2005) while others invoke executive attention control/capacity as one of multiple sources of variation in complex memory span performance (Baddeley, 2003; Barrouillet & Camos, 2001; Conway & Engle, 1996; Kane, Bleckley, Conway, & Engle, 2001). The former view implies that attentional capacity determines the activation of elements in working memory above a particular threshold. Such activation makes the elements readily accessible and available to the focus of attention. The latter view implies that active maintenance of information in working memory invokes domain-specific and/or domain-general resources depending on individual differences in ability and the task at hand (Baddeley, 2003; Conway et al., 2005). More importantly, research groups differ on a second fundamental issue of whether the predictive value of working memory tasks lies exclusively in the domain-general (executive) attention component of the task (Conway, Kane, & Engle, 2003; Daneman & Carpenter, 1980; Kyllonen & Christal, 1990; Turner & Engle, 1989) or is also constrained by the domain-specific requirements of the task. It is important to point out here that (executive) attention is a complex construct comprised of a set of different components (Baddeley, 1996; Morris, 1994).
Relatively few research studies have addressed specific executive attentional aspects of children’s complex memory span performance (St Claire-Thompson & Gathercole, 2006; Towse & Mclachlan, 1999; Zoelch, Seitz, & Schumann-Hengsteler, 2005). These studies have addressed the fractionated functions of the central executive as proposed by Baddeley (1996). These functions (examined using a range of tasks) include: co-ordination of simultaneous tasks, control of strategies, selective attention and inhibition, and retrieval and manipulation of information from the long-term store (Baddeley, 1996; St Claire-Thompson & Gathercole, 2006; Towse & Mclachlan, 1999; Zoelch et al., 2005). It appears that children’s performance on several of the tasks used, show different developmental trends. Overall, the studies suggest that there are several subcomponents of the central executive, which singly as well as in combination could influence complex memory span performance depending on the specific nature of the complex memory span task demands. Other studies have indirectly assessed the role of attention using several manipulations of the cognitive load of complex memory span tasks (Barrouillet et al., 2009; Cowan et al., 2005; Portrat, Camos, & Barrouillet, 2009) While attention functions are clearly present in children further research is required to develop tasks suitable to tap specific executive functions.

Considering the paucity of research explicitly examining executive attention mechanisms in children’s complex memory span performance, preliminary studies in our laboratory have begun to investigate the role of attention allocation in complex memory span performance (Magimairaj, Montgomery, Marinellie, & McCarthy, 2009). Extending the work of Bayliss et al. (2003, 2005), we examined the relative contribution of
allocation along with short-term memory storage and processing speed, to school-age (6- to 12-year-old) children’s complex memory span. Allocation refers to an individual’s ability to flexibly devote different amounts of attentional resources to two or more concurrent mental activities at once (Baddeley, 2003). We reasoned that a complex memory span task, because it entails concurrent storage and processing, should involve allocation. Results showed that storage and processing speed each contributed unique amounts of variance to complex memory span performance, similar to Bayliss et al. (2005). Attention allocation significantly correlated with complex memory span, even after controlling for age. However, it failed to account for any unique variance beyond short-term memory storage, probably because the allocation and short-term memory tasks both entailed similar storage requirements. These findings motivated further, in-depth exploration of the potential attention control mechanisms in children’s complex memory span.

Given the nature of complex memory span tasks, perspectives from existing models of working memory, and results from studies in both children and adults, it is evident that (executive) attention must also play a critical role in children’s complex memory span performance (Baddeley, 1996, 2003; Barrouillet, Bernardin, & Camos, 2004; Barrouillet et al., 2009; Conway et al., 2005; Cowan, 1995; Cowan, Nugent, Elliott, Ponomarev, & Saults, 1999; Cowan et al., 2005; Kane et al., 2001; Lepine, Bernardin, & Barrouillet, 2005; St Claire-Thompson & Gathercole, 2006; Zoelch et al., 2005). Also, because attention, like working memory, improves with age (Gomes, Molholm, Christodoulou, Ritter, & Cowan, 2000; Morris, 1996; Pearson & Lane, 1991),
it is likely that children’s working memory is associated with their developing attention abilities (Zoelch et al., 2005). For instance, attention is regarded as being fundamental to various cognitive skills such as play and language (Jones, Rothbart, & Posner, 2003; Spaulding, Plante, & Vance, 2008). It has also been suggested that low working memory capacity in children frequently co-occurs with inattentiveness, distractibility and lack of monitoring (Gathercole et al., 2008).

Given the lack of studies empirically examining the hypothesized role of attention control functions in children’s complex memory span, in the current study, using a psychometric approach, we investigated the potential role of two attention control mechanisms in the complex memory span performance of children between 7-11 years. The two attentional mechanisms evaluated were sustained attentional focus and attentional focus switching. Sustained attention is the ability to maintain attentional focus over a given period and is typically assessed by the ability to make accurate stimulus detections over time (Gomes et al., 2000). Both auditory and visual continuous-performance tasks were used to measure sustained attentional focus. Attentional focus switching was indexed by auditory and visual attentional focus switching tasks. Children’s complex memory span performance was assessed using a conventional listening span task and a counting span task. Two tasks for each construct were used to obtain a psychometrically robust measure for each.

It was predicted that both sustained attentional focus and attentional focus switching would contribute significant and unique amounts of variance to complex memory span performance after adjusting for age effects. Sustained attentional focus was
predicted to be critical to overall task performance because children must maintain
sufficient vigilance over the course of the task, but attentional focus switching was
predicted to account for the greater amount of variance. This is because complex memory
span performance should require the children to rapidly switch their focus of attention
between processing and storage, as has been suggested in the literature (Barrouillet et al.,
2004; Barrouillet et al., 2009; Unsworth & Engle, 2008).
CHAPTER 2: REVIEW

Several different theoretical views of working memory exist. Baddeley and colleagues (Baddeley & Hitch, 1974; Baddeley, 1986, 1990, 2000) suggested that working memory comprises a domain-general mechanism (i.e., central executive) that coordinates information in two different domain-specific storage devices, one devoted to verbal information (phonological loop) and the other to visuospatial information (visuospatial sketchpad). The executive is the mechanism that is responsible for coordinating working memory resources and monitoring the flow of information between the two storage devices (Baddeley, 2000; Baddeley, Emslie, Kolodny, & Duncan, 1998). The executive also serves important regulatory functions such as controlling the retrieval of information from long-term memory (including the language system) and attention control. There are several important attention control functions. One function is the ability to allocate attention to different dimensions of a task. Because many cognitive tasks entail two or more mental activities there is the need for individuals to effectively allocate their finite attentional resources (or mental energy) to each activity. Baddeley (2000) has also proposed a fourth component to his model, the episodic buffer. The buffer is presumably responsible for integrating (binding) information from the auditory and visual modalities into a coherent integrated representation or episode.

Other researchers argue for a domain-general view of working memory (Engle, Kane, et al., 1999; Engle, Tuholski, Laughlin, & Conway, 1999) in which working memory capacity is constrained by an individual’s attention control and ability to allocate attentional resources in the face of interference or distraction. Similar to Baddeley (1990,
2000), these authors also propose domain-specific storage devices. While the Baddeley model and the model of Engle and colleagues are similar with respect to their inclusion of a domain-general attention controller and domain-specific storage devices (see Figure 1), the two models part company regarding whether the storage devices are predictive of cognitive abilities. Engle and associates argued that controlled attention predicts cognitive processing and learning (see Figure 2a), whereas Baddeley and colleagues suggested the combination of the central executive and the two storage devices predicts cognitive processing and learning (see Figure 2b). A third view of working memory has been expressed by Miyake and colleagues (Shah & Miyake, 1996). They proposed a system that comprises two separate pools of domain-specific resources, one for verbal information and another for visuospatial information, with each domain having the ability to manipulate, process, and store information.

Figure 1. Schematic representation of working memory having multiple sources of variation: Domain-specific as well as domain-general constraints.
Figure 2. Schematic depiction of contrastive views on the predictive value of working memory.

Like adults, children’s working memory is measured by performance on complex memory span tasks (Case, Kurland, & Goldberg, 1982; Pickering & Gathercole, 2001; Towse, Hitch, & Hutton, 1998). For instance, in verbal span tasks (e.g., listening span), children are presented blocks of sentences for which they are asked to process the meaning of each sentence while they try to remember the last word in each sentence. Immediately following the last sentence in a block the children are asked to recall as many sentence-final words as they can. In nonverbal span tasks (e.g., counting span), children are presented a series of cards and asked to count the number of dots appearing on each card. After the last card in a set has been presented the children are asked to recall the number of dots they saw on each card. Such complex memory span tasks thus
invite children to allocate their attentional resources to both information processing (comprehending sentence meaning or counting the number of dots) and information storage (remembering words or number values). Complex memory span is defined as the number of items that are accurately recalled or the longest list-length of items accurately recalled.

Individual Factors Constraining Children’s Complex Memory Span Performance

The developmental memory literature makes clear that children’s complex memory span performance improves with age (Barrouillet & Camos, 2001; Bayliss et al., 2003, 2005; Case et al., 1982; Towse et al., 1998). An important theoretical issue has centered on what underlying factors of working memory may constrain their complex memory span performance. The two candidate factors most explored include processing speed and short-term storage (Bayliss et al., 2003, 2005; Hitch, Towse, & Hutton, 2001; Towse & Hitch, 1995; Towse et al., 1998).

One of the first studies to address the nature of the developmental improvement in children’s complex memory span was conducted by Case et al. (1982). These investigators presented children a counting span task in which they counted the number of dots on a series of cards and then later recall the number of dots on each card. The number of cards to be counted varied across trials (i.e., 3-8 cards), and as a consequence the number of values to be recalled after counting varied. As predicted, the older children yielded a larger counting span than the younger children and complex memory span was significantly correlated with the speed with which the children counted the dots. Case et al. argued that age-related improvements in complex memory span are the result of more
efficient processing (i.e., operational efficiency) rather than increases in overall working memory capacity (i.e., storage). That is, during development, children’s basic processing operations become faster and more efficient with experience. The consequence is that more efficient processing leaves more working memory resources available for storage. From their findings, a resource-sharing model of working memory was proposed in which it is assumed that a single pool of resources is available to perform complex memory span tasks, with processing and storage functions both drawing upon the same pool.

Processing speed has been the focus of considerable developmental cognitive research. Some researchers have argued that processing speed is a fundamental and stable cognitive trait of children and adolescents underlying much of cognitive growth (Hale, 1990; Kail, 1991, 2000). Processing speed refers to processing efficiency or rate (Kail & Salthouse, 1994; Salthouse, 1996) and emphasizes the amount of cognitive work that can be completed in a given unit of time. An underlying assumption regarding processing speed is that it is dependent on “neural processing speed” (e.g., Cerella & Hale, 1994; Jensen, 1993), i.e., rate of synaptic transmission. The basic idea is that those individuals with faster processing are better able to remember and/or process greater amounts of information in the same unit of time than slower processing individuals. The cognitive literature indicates that processing speed improves with age, becoming markedly faster from early childhood through adolescence and into young adulthood (Fry & Hale, 1996; Hale, 1990; Kail, 1991, 1992, 2000; Kail & Miller, 2006). Declines in processing speed in old age have also been reported (Nettelbeck & Burns, 2010; Salthouse, 1991). It has
been argued that age-related changes in processing speed have direct effects on cognitive performance as well as indirect effects by influencing those processes supporting cognitive performance.

The role of processing speed in children’s complex memory span performance has been explored by a number of investigators (Bayliss et al., 2003, 2005; Hitch et al., 2001; Towse & Hitch, 1995; Towse et al., 1998). Towse and colleagues, for example, argued that individuals perform complex memory span tasks by rapidly alternating their attentional resources between processing and storage (i.e., task switching hypothesis) such that, when they are performing the processing component, the items stored in short-term memory may begin to fade. That is, the stored items suffer time-based forgetting. On this view, processing speed has an indirect influence on complex memory span performance because it mediates the interval during which the stored items may begin to fade. Towse et al. evaluated this hypothesis by presenting 6- to 11-year-olds various complex memory span tasks (i.e., reading, counting, operation) in which processing complexity was held constant but the retention interval (i.e., temporal duration of item storage) was systematically varied. This design allowed the authors to assess the contribution of the retention interval unconfounded by processing complexity. The authors found an inverse relationship between complex memory span and retention interval. Span significantly declined when the retention interval increased. Based on these findings, Towse and colleagues argued that processing speed and retention duration are more important to children’s complex memory span performance than processing complexity.
A second factor potentially influencing children’s complex memory span performance is short-term memory storage. Interestingly, while much is known about the development of short-term memory and factors potentially relating to developmental increase in short-term memory capacity (Chuah & Mayberry, 1999; Cowan, 1988, 1995; Fergusson & Bowey, 2005; Gathercole, 1999; Gathercole, Pickering, Ambridge, & Wearing, 2004), relatively little is known about the role of short-term memory in children’s complex memory span performance. The majority of the work examining the influence of short-term memory has been conducted in the context of how processing speed and the duration of the retention interval affect storage (Towse & Hitch, 1995; Towse et al., 1998). Studies that include independent measures of short-term memory and examine their contribution to children’s complex memory span are relatively few in number (Bayliss et al., 2003, 2005). The role of short-term memory will be addressed below in the section “Research Examining the Effects of Multiple Working Memory Mechanisms on Children’s Complex Memory Span”.

A third candidate factor potentially influencing children’s complex memory span is attention. This factor has received little empirical research focus in the developmental literature (Towse & Houston-Price, 2001; Zoelch et al., 2005). Attention is a complex mental construct that is generally defined as one of the stages of information processing, which allows an individual to select entities that need to be processed, and continually provides the focus and resources needed for successful task completion. While attentional capacity refers to the finite amount of mental energy available to the working memory system for information processing and storage, attention control/allocation refers to an
individual’s ability to flexibly use his/her resources during cognitive processing (e.g., dividing or allocating attentional resources between two or more concurrent mental activities such as verbal processing and verbal storage). Attention also consists of various subcomponents, for example, sustained attentional focus and selective attention (e.g., Morris, 1996). Though the role of attention in working memory has always been emphasized in the literature, different investigators conceptualize this relation in different ways (Baddeley, 1998, 2000; Barrouillet & Camos, 2001; Barrouillet et al., 2004, 2009; Cowan et al., 2005; Just & Carpenter, 1992; Kane et al., 2001). Some of these conceptualizations are described below.

Conceptualizations of Executive Attention Skills Within Working Memory

In current conceptions of working memory, it is indispensable to consider both structural and functional constraints in performance. For example, there is not only a capacity limited attentional constraint that determines the number of items that can be held in working memory, but also an attention control function(s), which can influence the way information is stored in and retrieved from working memory. While attentional capacity has been consistently indexed as the number of units or “chunks” that can be held in the focus of attention, attention control has been conceptualized in multiple ways. Attention control within working memory has been conceptualized for example as attention allocation, inhibition and attention switching (Awh, Vogel, & Oh, 2006; Baddeley, 2000; Barrouillet et al., 2004, 2009; Cowan, 1995; Hasher, Lustig, & Zacks, 2008; Lepine, Bernardin, et al., 2005; Towse et al., 1998; Turner & Engle, 1989;
Unsworth & Engle, 2008). The following sections discuss some of the known structural and functional attentional constraints related to working memory.

**Role of Attentional Capacity**

Barrouillet and Camos (2001) have suggested that attentional capacity influences children’s complex memory span. These authors argue that the increases in overall resources allow children to allocate sufficient attention to both processing and storage. They also argue that the processing component of complex memory span tasks (i.e., the nature of processing) is more important to performance than overall retention interval. Specifically, storage suffers not just because of the duration of the retention interval (Towse & Hitch, 1995; Towse et al., 1998), but because the processing activity (especially more difficult processing) draws on the children’s attentional resources and prevents them from refreshing the items stored in short-term memory (Gavens & Barrouillet, 2004). Thus, relative to older children, younger children have less attentional resources to support both processing and storage.

Barrouillet and Camos (2001) showed that, relative to simpler processing activities, more difficult processing activities lead to greater declines in complex memory span, even when the total duration of the two processing activities are held constant. Children completed a complex memory span task that included two conditions. In one, children performed a continuous operation span task in which they performed a series of simple math operations (4, +1, +1, -1, +1) while at the same time they had to remember a series of letters that appeared one at a time at the end of each operation. In the second condition (*baba* span), instead of performing the math operation, children merely had to
repeat the syllables “baba” for the same duration that the children took to complete the
math operations. Children had to remember the letter that appeared at the end of each
sequence of a “baba” repetition. In both conditions, letters to be remembered increased
in list length as the number of operation sequences (or “baba” sequences) increased in
length. In both conditions, the amount of time for the “processing” activity was fixed. It
was found that the mean number of letters recalled in the continuous operation task was
lower than the number of letters recalled in the baba task. These results were taken to
support the claim that complex memory span is determined not by the duration of
processing but the complexity of processing. In this case, completing simple math
operations was more attention demanding than repeating baba.

Cowan (1995, 1999) described an integrated/embedded model of working
memory that explicitly incorporated attention. According to this framework, working
memory capacity is the limit of the number of items/chunks that are in the focus of
attention at a given point in time, without any opportunity for rehearsal or use of
mnemonic strategies; this number is estimated to range from 3 to 5. That is, working
memory is the activated portion of short-term memory that is in the focus of attention,
and short-term memory, in turn, is embedded within long-term memory. Cowan and
colleagues also suggested that working memory capacity is best reflected by the storage
and retrieval of unattended items residing in working memory. That is, working memory
capacity represented the number of automatically encoded and stored items that were
deliberately brought back into the focus of attention during recall. By contrast, active
attention (as driven by the use of mnemonic and recoding strategies) produced an
overestimate of working memory capacity, for example the magical number 7 as proposed by Miller (1956).

In several experiments with children and adults, Cowan and colleagues have demonstrated that the processing component of complex memory span tasks prevents individuals from rehearsing the to-be-recalled items. This leads to reduced storage/recall relative to conditions in which rehearsal is permitted between storage episodes. Cowan and colleagues suggested a dimension of attention called scope of attention instead of control as used by other researchers. They argued that control of attention differs across measures and also does not reflect a meaningful measure of working memory capacity. According to Cowan, scope of attention is a more useful measure of working memory capacity, because it theoretically and empirically relates to processing and storage; scope of attention reflects the ability to “zoom-in” or “zoom-out” one’s focus of attention (which is limited in capacity) in the presence of interference or processing.

Cowan and colleagues have provided converging evidence to demonstrate that, no matter what distracting task is used to divert attention during stimulus encoding and maintenance, working memory capacity is limited to 3-5 units or chunks (Cowan, 2001). For example, they presented for later recall visual arrays with many distractors or auditory arrays, which were very rapid and unpredictable. Similarly, diverting attention away from to-be-remembered stimuli was achieved through dichotic listening memory tasks where selective attention was required towards one channel while the other channel had to be ignored. Because all of these conditions prevented rehearsal or grouping in memory, they reflected subjects’ true scope of attention (i.e., core estimate of working
memory capacity). This core estimate of working memory was consistent across tasks and was found to improve with age.

Various other researchers, using a dichotic listening paradigm, support Cowan’s postulation of the focus of attention being critical to working memory (Colflesh & Conway, 2007; Conway, Cowan, & Bunting, 2001; McElree, 2001; Oberauer, 2002, 2003). This paradigm involves simultaneous presentation of two different stimuli, one to each ear. In the Conway et al. (2001) study, participants shadowed (repeated) the input presented to one ear while ignoring the input to the other. In a study by Colflesh and Conway (2007), participants shadowed the input to one ear but also listened for their own name presented to the opposite ear. In each of these studies, individuals with high working memory capacity demonstrated better ability to flexibly control their focus of attention (whether it was selectively ignoring stimuli or dividing attention between two stimuli) in comparison to persons with low working memory capacity. According to Cowan and colleagues focus or scope of attention theoretically and empirically appeals to the concept of working memory. This is because, scope of attention reflects the number of items that can be held in memory at a given moment in the absence of rehearsal/chunking strategies, achieved by the continuous processing component of the complex memory span task.

Cowan and colleagues also emphasized the role of attentional capacity in developmental increases in complex memory span by referring to memory search processes as one of the mediating factors (Cowan, 1992; Cowan et al., 1994). According to Cowan and colleagues memory search processes may become faster with development
owing to increases in attentional capacity. Such search processes during silent periods of recall likely serve to reactivate or refresh items for retrieval.

**Role of Attention Control**

Baddeley and colleagues proposed one of the earliest models of working memory. Their multi-component model is comprised of two storage components (phonological loop, visuospatial sketchpad) and a central executive control function (Baddeley, 1986, 1990; Baddeley & Hitch, 1974). The phonological loop temporarily stores incoming speech while the visuospatial sketchpad temporarily stores incoming visual information. More recently a new component known as the episodic buffer has been added to the Baddeley model (Baddeley, 2000, 2003). The episodic buffer is regarded as an interface between the two storage components wherein auditory and visual inputs are integrated into a single coherent representation or “episode.”

The central executive is regarded as a domain-general system that functions as an attentional supervisor or cognitive gatekeeper. One main function of the executive is to coordinate the flow and retrieval of information between the storage buffers and the retrieval of information from the language system during language comprehension and production. Specific attention control functions attributed to the executive include: allocating attentional resources to more than one dimension of a task, rapid switching of attention between task dimensions, planning, inhibition, updating of information, selective attention, focused sustained attention, multiple task coordination, task monitoring, and utilizing task feedback (Anderson, 1998; Baddeley, 1996; Morris, 1996). The central executive coordinates one or more attentional functions while individuals
perform the processing and storage activities of a complex memory span task. According to the literature, the central executive has been the least clearly specified aspect of the Baddeley model thus far (Baddeley, 1996; May, 2001; Towse & Houston-Price, 2001). Most empirical studies that have investigated the central executive component of the Baddeley model (e.g., using dual task coordination, random generation, selective attention) have been restricted to studies in adults and in patients with frontal lobe dysfunctions (e.g., Baddeley, 1996; Baddeley et al., 1998; Emerson, Miyake, & Rettinger, 1999).

The few developmental studies that have addressed executive functions, clearly suggest that the executive is not a unitary construct but rather multi-dimensional in nature (St Claire-Thompson & Gathercole, 2006; Towse & Mclachlan, 1999; Zoelch et al., 2005). We would like to point out here that while St Claire-Thompson and Gathercole (2006) have directly addressed the contribution of some executive functions to complex memory span performance, the two latter studies (Towse & Mclachlan, 1999; Zoelch et al., 2005) have mainly focused on exploring various central executive functions as defined by Baddeley.

Another theoretical viewpoint of working memory (Engle, Cantor, & Carullo, 1992; Kane et al., 2001; Turner & Engle, 1989) suggests that domain-general controlled-attention is a critical predictor of complex memory span. According to these authors, persons with high span are able to maintain more items in storage while simultaneously performing a secondary task, and such performance requires controlled and flexible attention toward each component of the task. In a series of studies, Kane et al. (2001)
demonstrated that individuals with high complex memory span outperformed low span
individuals in experiments involving attention control as measured by speed and accuracy
on antisaccade tasks. Saccadic movements of the eye are rapid eye movements between
fixations, based on abrupt onset visual cues. This task is frequently used as an index of
controlled-attention because it is a simple nonverbal task invoking minimal memory
requirements. In antisaccade tasks, a target appears opposite the cued location, thereby
requiring the individual to flexibly control attention in order to inhibit reflexive responses
towards the cued spatial location. On the other hand, on prosaccade tasks the target and
the cue appear on the same location. In a series of such experiments, Kane and
colleagues found that individuals with high and low complex memory spans performed
equally well on prosaccade tasks. However, differences emerged on antisaccade tasks
where individuals with low complex memory span performed significantly poorer than
high span individuals. The authors thus concluded that high span individuals have better
controlled-attention skills and that the controlled-attention component of complex
memory span tasks makes them better predictors of higher-level cognitive abilities than
simple span or storage tasks. According to the authors, controlled attention is the
outcome of activation of a general capacity and predicts tasks that require controlled
processing better, than tasks that require automatized processing (Conway & Engle,
1996). Engle and colleagues also suggested that complex memory span tasks require
controlled attention, particularly switching attention between the processing and storage
(to reactivate storage) components or to inhibit interfering or distracting stimuli towards
successful completion of task goals (Unsworth & Engle, 2007). Related to the above
viewpoint by Engle and colleagues a series of studies by other investigators also emphasize the role of attention control in complex memory span performance (Barrouillet et al., 2004, 2009; Hashler et al., 2008).

The foregoing discussion highlights the major theoretical viewpoints that discuss the role of attention control in working memory. Executive attention control functions have since been measured and described using different approaches, and have been shown to correlate with better complex memory span performance. Some of the approaches have addressed multiple executive functions while others have limited investigations to a single attention control construct. These approaches are described below.

*Studies on Multiple Executive Functions*

Zoelch et al. (2005) focused on examining the multiple processes of the central executive as proposed by Baddeley (1996). Multiple executive functions in children between 5 to 10 years of age and young adults were studied using several tasks such as random generation, mental fusion, trail-making, decision-making, Stroop, color span backwards and visual decision span. Random generation for example, involved selection of unconnected responses such that the role of memory representation was minimized. Random generation was originally assumed to be a good index of domain-general attention control and retrieval (Baddeley et al., 1998). Children in the Zoelch et al., study were asked to randomly produce one of 4 numbers (1, 2, 3, and 4). They were required to do so while imagining that one of four balls was taken out from a bag (and placed back). Each child produced a series of 60 numbers within 2 minutes. Responses were evaluated
for number of productions and the quality of the productions (e.g., younger children produced more stereotyped responses like 2, 3, 4 owing to poorer inhibitory skills). On the Stroop task children saw pictures of vegetables shown in noncongruent colors. They were required to name the original color of the vegetable as quickly as possible. The Stroop task was assumed to tap selective attention, inhibition, and decision-making, and was indexed by reaction time and accuracy. On the trail-making test children were required to connect yellow and green dots alternately in ascending order of their size, as fast and accurately as possible (i.e., connect a yellow and green dot of the same size then connect the next larger yellow dot followed by the green one, and so on). This task was thought to tap task switching and was evaluated by solution times. The mental fusion task primarily indexed manipulation of and access to long-term memory. It involved children seeing one object image (e.g., triangle) followed by another (e.g., semi-circle). In the third step the first object was presented again and the child was asked to mentally join the pictures together to report what they thought they saw (e.g., “a sailing boat”). Accuracy of fusion was the primary outcome on this task. The decision-making task assessed selective attention and inhibition. Children reacted with a “yes” response if a search criterion appeared with the presented stimulus and a “no” if it did not (e.g., of a search criterion – “Look out for the yellow ball”). Accuracy of responses and reaction times were the outcomes.

For the complex span measures, the authors used color span backwards and visual decision span. On the color span task children saw buttons of different colors (monosyllabic names) in a particular sequence and were asked to recall the sequence in
reverse order. In the visual decision span task, pictures of objects were presented to the children and they were first asked to report if the object was edible or not. Following the end of the object list, children were required to recall the objects in the same order that they were presented. Both these tasks were indexed by recall accuracy. The two tasks were assumed to measure the control of strategies for encoding and retrieval, selective attention, and inhibition.

The essence of the findings from the study by Zoelch et al. (2005) was that the central executive is fractionated with separable as well as interactive subfunctions that show different developmental trajectories in children. According to the authors, each of the four executive functions suggested by Baddeley (1996); coordination of simultaneous tasks, control of strategies, selective attention and inhibition, and retrieval and manipulation of information from the long-term store, have different developmental trajectories. That is, while performance on some tasks showed a linear growth (e.g., Stroop, trail-making) other more complex tasks (e.g., color span, visual decision span) needed further investigation in children older than 10 years but younger than adults to delineate (nonlinear) developmental trajectories. Also, while correlations were significant between some of the tasks that shared common mechanisms (color span backwards, decision-making and the Stroop strongly shared selective attention and inhibition), there were tasks such as random generation that showed poor correlations with other central executive tasks. This is consistent with the Towse and Mclachlan (1999) suggestion that the random generation task is complex and multiply determined. Thus, correlations among the tasks reflected the theoretical assumptions of the functions subserving those
tasks and that each task measured more than one central executive function. Domain-specific factors of the tasks were not addressed in this study (Zoelch et al., 2005). The authors concluded that while there is a continued need to explore a variety of methods to assess central executive processes, it remains to be explored which of these multiple control processes play the most critical roles in working memory, and to what extent involvement of these processes depends on the given cognitive task.

Another study on typically developing children between the ages of 11 and 12 years examined multiple executive functions (such as shifting, updating, and inhibition) and their relation to working memory and academic achievements (St Claire-Thompson & Gathercole, 2006). Multiple tasks were used for each executive measure and working memory. For example, one of the shifting tasks was a plus-minus task. Three lists of 30 two-digit numbers were used. On one list, children had to add 3 to each number. On the second list, children had to subtract 3 from each number, and, on the third list, they had to alternate between adding and subtracting 3 from the numbers. Children were instructed to complete as many items as possible on each list within 2 minutes. Shifting costs were measured as the difference between performances on alternating and repeat trials. One of the updating tasks used was the letter memory task in which letters were presented visually in a series. Letters were presented for 2000 ms each and the number of letters varied randomly across trials (5, 7, 9, or 11). Children had to recall the last four letters presented on each list. Finally, the Stroop task was one example of the tasks used to measure inhibition. Children were presented with color words in incongruent colors, for example, RED in green ink, and were asked to name the color of as many stimuli as
possible within 2 minutes. For working memory, both verbal and visuospatial span tasks were used. Overall, the results revealed that updating and inhibition were separable processes. However, only updating correlated with working memory. Shifting was not identified as a separable executive skill probably because of methodological limitations (e.g., task design and reliability).

Studies on a Single Executive Function

Attention allocation. Children’s age-related improvement in attention allocation (not just increased capacity) has been demonstrated using dual task paradigms. Dual task paradigms involve performance on two tasks simultaneously such that allocation of attentional resources to each of the two is required. For instance, Irwin-Chase and Burns (2000) presented second and fifth grade children two kinds of dual processing tasks. In one condition, each of the two tasks was designated as having equal priority; in the other condition, one task was designated as primary and the other as secondary (unequal priority condition). The assumption behind the design was that the unequal priority condition invited children to allocate their attentional resources flexibly in accordance with the priorities of the task. In the equal priority condition, there were no priorities to guide the children’s allocation of attention. It was predicted that the older children should show better dual-task performance in the unequal priority condition because they should have greater control of attention than the younger children. The children also completed a single processing task as an index of attentional capacity. Overall, results were consistent with the authors’ hypotheses. After controlling for single task performance, both age groups performed similarly in the equal priority condition, but the older children
performed better than the younger children in the unequal priority condition. These results were interpreted to suggest that older children have greater control of their attention than younger children. Similar findings regarding children’s attentional resource allocation abilities in dual-tasks have been reported in other studies as well (Karatekin, 2004; Karatekin, Couperus, & Marcus, 2004; Karatekin, Marcus, & Couperus, 2007; Schiff & Knopf, 1985).

Investigators have also addressed the issue of attentional allocation in children by considering performance on simple span tasks vs. performance on the same span tasks in the presence of a secondary task requirement. Hale, Bronik, and Fry (1997) investigated performance of 8- and 10-year-old children and young adults on memory span tasks (digit/letter/location recall) with and without a secondary task requirement. The secondary task was saying aloud the name of the item color (verbal) or indicating the item color on a palette (visuospatial). Both verbal and spatial span tasks were used singly and with secondary task requirements from each domain. For example, a verbal span task was paired, first, with a verbal secondary task and, next, with a spatial secondary task. Overall, results suggested that children’s performance deteriorated when there was a secondary task requirement associated with the simple span task. This interference was greater in the younger children in comparison to older children. Older children’s performance was poorer mainly when the primary and secondary tasks were from the same domain. While younger children also showed greater interference with secondary tasks from the same domain as the primary tasks, they were also affected significantly in the crossed domain condition unlike the older children. This was taken as evidence to
suggest that the central executive (allocating attention between primary and secondary tasks) was still immature in 8-year-olds but demanded little executive resources in older children. According to the authors, these findings were consistent with developmental research that suggested increases in complex memory span with age (Gathercole, 1999; Gathercole et al., 2004)

Inhibition. Inhibitory processes have been extensively studied in the adult memory literature and findings generally converge with (a) the work by Engle and colleagues who regard working memory as being equivalent to a controlled (executive) attention system and also with (b) the central executive component of the Baddeley model (Baddeley, 2003; Friedman & Miyake, 2004; Kane et al., 2001; Lustig & Hasher, 2002; May, Hasher, & Kane, 1999). In the context of complex memory span, inhibitory processes help prevent irrelevant information from entering into the focus of attention, delete information that is no longer relevant and also stop pre-potent responses (e.g., habitual responses from previous trials) from gaining access to the focus of attention. Conway and Engle (1994) did not rule out the possibility that the reduced ability to inhibit as one becomes older might be a result of reduced overall attention resources in addition to reduction in attention control.

Friedman and Miyake (2004) studied the relation of three inhibitory functions to working memory in adults using a range of tasks for each function. The three functions studied were prepotent response inhibition, resistance to distractor interference (e.g., selectively ignoring irrelevant stimuli that may be introduced during the course of the task), and resistance to proactive interference (e.g., difficulty recalling newer elements
due to interference caused from previously recalled elements in memory). While the former two seemed to be related, resistance to proactive interference appeared to be distinct from the other two functions. Also, resistance to proactive interference was found to predict reading span. This was consistent with findings from Bunting (2006) who found that resistance to proactive interference was important to complex memory span. Overall, the role of resistance to proactive interference has been found to be consistent with the controlled-attention view of working memory and appears to influence the predictive utility of working memory (Bunting, 2006). Because all of the above studies are from the adult literature, we have restricted our discussion here to the theoretical viewpoints only and excluded the methodological details about these studies.

There are few studies that have explored inhibitory mechanisms in children’s complex memory span performance. The extant literature primarily includes studies of children with atypical development, such as children with language impairment, attention-deficit hyperactivity disorder, or autism, which is beyond the scope of the present review (Bishop & Norbury, 2005; Im-Bolter, Johnson, & Pascual Leone, 2006; Marton, 2007; Marton, Kelmenson, & Pinkasova, 2007; Noterdaeme, Amorosa, Mildenberger, Sitter, & Minow, 2001). The few studies with typically developing children (St Claire-Thompson & Gathercole, 2006; Zoelch et al., 2005) have been discussed earlier in this section in reference to multiple executive functions. Overall, our review on this aspect suggests that inhibition is a difficult construct to measure because task performance on so-called inhibition tasks could be influenced by multiple processes (Friedman & Miyake, 2004). Latent variable analyses are the primary solution to this
issue. There is also clearly a need for new measures to assess the role of inhibitory processes in children’s complex memory span. This is because the inhibition tasks currently being used (e.g., standard psychological test batteries, stop-signal tasks, Stroop tasks, go-no go tasks) seem to assess inhibitory control but in a way that is fundamentally different from how inhibitory control is invoked in complex memory span tasks. That is, while these tasks predominantly appear to tap behavioral inhibition, what is really needed are tasks that measure cognitive inhibition (Friedman & Miyake, 2004; Harnishfeger, 1995).

Attentional focus switching. Serial allocation of attention to items in memory has been proposed by some earlier information processing approaches (e.g., Sternberg, 1969). Serial allocation implies that attention can be given to only one aspect of a task at a time. Such an approach delineates that attention is serially switched between items in memory and that items cannot be accessed simultaneously. This was demonstrated in a series of experiments where individuals needed to determine if an item presented belonged to an earlier presented list or not. As the lists became larger, the reaction times to make such comparisons increased, thus implying that an individual comparison of the target with each item in the memory set was required (Garavan, 1998). While some memory scanning experiments are in consonance with such a serial attention switching perspective (Schiffrin & Schneider, 1977; Schneider & Schiffrin, 1977), others favor a parallel processing model according to which multiple items in memory can be accessed simultaneously (Ratcliff, 1978). Results from these latter studies are taken to suggest that
individuals, rather than rapidly switching their attention between storage and processing, are able allocate sufficient attention to both at the same time.

Few developmental studies have addressed attentional focus switching in children. Pearson and Lane (1991) conducted a developmental study on auditory attention switching. They studied 8-year-olds, 11-year-olds, and young adults. Using a dichotic listening task, they examined attentional reorienting when children were asked to report target stimuli (numbers/letters) from one ear. Two types of signals (high tone/low tone) were used to refer to which ear (left/right) children needed to attend to. The successive signals either indicated children to continue listening from the same ear (no-switch condition) or indicated children to switch their attention to the contralateral ear (switch condition). Performance was assessed based on the number of target stimuli omitted, intrusion errors (stimuli reported from the irrelevant channel) and total errors for each condition. Interestingly, 8-year-old children’s performance was identical to the 11-year-olds in the no-switch condition but was significantly worse in the switch condition. Even though the 8-year-olds did not perform as well as the older children, they demonstrated the ability to switch their attention to a second source when instructed. While the 11-year-olds were faster and more accurate than the 8-year-olds on attentional switching, they did not differ significantly from the adults. Results from this study indicated that, attentional switching skills improve with age in children, especially in the early school years, and likely plateau to adult-like performance by 12 to 13 years of age.

The attention switching perspective has been extended to complex memory span tasks where attention is likely switched between the storage and processing episodes
within a task. Attention switching during complex memory span tasks in children was first suggested by Towse and colleagues (Towse & Hitch, 1995; Towse et al., 1998). However, this issue has seen little empirical evaluation except for the single study by St Claire-Thompson and Gathercole (2006; see above under Multiple Executive Functions). Some studies in adults have looked at attention switching through focus or task switching experiments. In such experiments, participants are assessed for their ability to accurately and rapidly switch their focus of attention between two dimensions of a given task (focus switching) or switch between two tasks (task switching). For example, focus switching is said to be involved when keeping a running count of two distinct stimuli that are randomly presented. In this case, one of the two items needs to be brought into/out of the focus of attention. Task switching, on the other hand, involves performing two different kinds of operations on items that are already in the focus of attention such as switching between adding and subtracting number stimuli presented in a sequence.

Garavan (1998) studied the attention switching process in working memory in a paradigm that involved updating two counts (entities). The counts to be kept in mind were of two different geometric figures (triangles-rectangles), with each figure being presented singly on a computer screen immediately followed by the other figure. Multiple predetermined sequences of the stimuli were presented. Stimulus sequences were such that they included both non-change and change presentations in each trial sequence. Participants worked at their own pace by pressing the space bar to deliver each stimulus. Non-change presentations were those in which the shape currently being presented was the same as the previous one. Change presentations were those in which the shape
currently being presented was different from the previous one. For each presentation, the participant updated both counts (i.e., kept a running count of each stimulus type) either overtly or covertly. Response-time difference between the change and non-change presentations revealed that participants were 300-500 ms slower on change presentations than non-change presentations.

In a follow-up experiment, Garavan, Ross, Li, and Stein (2000) used a small and big square as the two objects rather than two different shapes. This was done to circumvent any potential perceptual confounds relating to one object (triangle/rectangle) being more salient or difficult than the other, which could have influenced the results of the first study. The computer automatically registered time taken to update the running counts. Switch costs were calculated as the overall reaction time difference between non-change and change trials and the overall accuracy of counts as a function of frequency of switches (change presentations). It was hypothesized that updating on change presentations would lead to greater reaction times when compared to non-change presentations and accuracy of counts would decrease as a function of frequency of change presentations. This was because attention on change presentations needed to be switched from a one kind of stimulus to another. Higher frequency of such switches, thus, was likely to have a detrimental effect on accuracy of counts as they invoked greater attentional resources.

Overall, the results revealed that counts on non-change presentations were updated faster than counts on change presentations. This was because change presentations were associated with attention switching costs, because attention had to be
switched from one stimulus to the other. By contrast, on non-change presentations there was no significant burden on the attentional system to update counts of objects that did not change. However, if equal amount of attentional resources were available concurrently to both types of stimuli, there would have been no difference between change and non-change presentations. The switch cost suggested that the two separate counts were maintained serially and were not accessible simultaneously in working memory. According to Garavan et al., (2000) such a switching paradigm reflects the controlled allocation of attentional resources within working memory.

In an adapted version of the Garavan paradigm, Unsworth and Engle (2008) examined attentional focus switching and task switching in individuals (young adults) with high and low complex memory span. The focus-switching task involved updating two counts (small and big squares) as described above. Task switching, on the other hand, involved updating the two counts based on one of two operations: addition or subtraction. Thus, the fundamental difference between focus switching and task switching was that in focus switching two different items were brought into/out of the focus of attention while in task switching two different tasks were performed on a set of stimuli that were in the focus of attention.

The two dependent variables were reaction time between stimuli presentations that were self-paced following each update, and accuracy of counting. Results revealed that switch costs (increase in reaction time and decrease in accuracy of counting) increased as a function of the number of switches in the type of operation (addition or subtraction) within a trial and the lag between the current and last update of a specific
type of square. Thus, in these experiments it was demonstrated that attentional switching was invoked for switching between two different types of tasks as well as between two types of stimuli within a single task.

Interestingly, however, when task switching and focus switching skills were used as predictors of higher-level cognitive functioning and working memory, investigators found that focus switching and not task switching predicted performance on higher order cognitive functioning (as indexed by performance on the *Raven’s Matrices*). Finally, accuracy of focus switching was related to performance on working memory and the *Raven’s Matrices*. Task switching and speed of switching were not. These results are intriguing. They imply that both task and focus switching invoke attention-switching costs but that there is something about focus switching that makes it a better predictor of higher-order cognitive functioning than task switching.

Results of more recent studies in adults investigating the relationship of task switching and focus switching to working memory and higher-order cognitive functioning appear to shed light on why focus switching is more predictive than task switching (Liefooghe, Barrouillet, Vandierendonck, & Camos, 2008; Verhaeghen & Basak, 2005; Verhaeghen & Hoyer, 2007). These studies have demonstrated that focus switching and task switching are distinct abilities that rely on different processes. Focus switching costs are attributed largely to retrieval processes in working memory. Focus of attention reflects the active state of items in long-term memory with the speed of item access varying depending on whether the items are inside or outside of the focus of attention. For instance, while items within the focus are retrieved rapidly, items outside
the focus need greater time to be accessed. This difference in the speed of access is measured by focus switching costs, where change trials involve accessing items outside the focus of attention and non-change trials involve accessing items that are already within the focus. Verhaeghen and colleagues compared focus switching to other control processes that likely incorporate switching, for example, task switching and updating the contents of the focus. In task switching, the task changes from trial to trial and there is no storage involved so there is no switching of items back and forth. During updating, the identity of an item stored in working memory is updated. That is, contents of the focus of attention are updated with items within or outside the focus. The results of their study revealed that focus switching is not related to either task switching or updating. The studies also suggested that whereas task switching is not age sensitive, focus switching is, but only for accuracy of switching and not speed of switching. Thus, switching processes in working memory are independent from control processes such as task switching and memory updating. Overall, available evidence suggests that attentional focus switching (as measured by accuracy of switching) is an important predictor of complex memory span performance.

While the present study was being conducted, the specific role of attentional switching in children’s complex memory span development was detailed in a new model of working memory capacity, the Time-Based Resource-Sharing model (TBRS; Barrouillet et al., 2009). Barrouillet et al., proposed the TBRS model as a hybrid model that combines processing load (Barrouillet et al., 2009; Portrat et al., 2009) and the proportion of time for which attention is switched away from storage to processing
The model is rooted in four main assumptions. First, both information processing and storage draw on the same limited pool of attentional resources. Second, only one attention-demanding step in a complex memory span task can occur at any given moment due to an inherent “bottleneck” in the use of central/attentional processes. For instance, if attention is captured by the processing activity, it is unavailable for storage. Third, immediately upon switching attention away from storage to processing, the stored items suffer activation decay and begin to fade. Stored items will fade completely if they are not refreshed. Refreshment occurs through reactivation, i.e., items are reactivated by being brought back momentarily into the focus of attention. Fourth, processing and storage share attention via a rapid, continuous, and alternating switching of attention between processing and storage. Functionally, as the proportion of time for which attention is occupied by processing increases (with more difficult processing activities requiring more attention), the duration of storage also increases, along with an increased probability that the memory traces of the items will begin to fade. It might help here to distinguish the views of Barrouillet et al. and Towse et al. (Towse, Hitch, & Horton, 2007) about attention switching. For Barrouillet and colleagues, attention switching occurs during the processing activity. According to Towse and colleagues, switching occurs between completion of each processing phase and the item presented for recall, referred to as micro-task switching.

At a broader level, the TBRS model is similar to the resource-sharing account given by Case (1985). According to Case et al. (1982), because storage and processing
rely on the same pool of resources, more efficient processing frees up resources for storage capacity. However, the resource-sharing mechanism proposed by Barrouillet et al. differs from that of Case at a more atomic level in that it specifies resource sharing using an attentional switching account instead of a processing efficiency account. While the TBRS model was elaborated earlier with data from adults (Barrouillet et al., 2004) the model was first tested in children by Portrat et al. (2009). While children (10-year-olds) maintained letters for recall, the processing load for a spatial location judgment activity was manipulated by varying target discriminability based on target location or figure-ground contrast. In the conditions in which discriminability was made harder (i.e., high processing load), both longer response times and reduced letter recall resulted. Thus, time-based attentional capture, which was greater in the high processing load condition, contributed to children’s poorer complex memory span. In their most recent study, Barrouillet et al. (2009) provide further support for the TBRS model. Children (7- to 14-year-olds) demonstrated greater attentional costs while switching from storage to processing in high processing load tasks as compared to low processing load tasks. Complex memory span performance was found to be a function of both the retention duration and the pace of the processing component. For example, though a faster paced processing activity led to shorter retention duration (i.e., stored items needed to be retained for shorter periods), a faster pace represented a high cognitive load because processing had to be completed in less time. Thus, a faster paced processing activity resulted in poorer complex memory span performance because it did not allow for frequent reactivation of the memory traces. Together, the authors provide evidence in
support of the TBRS model in children in which both retention interval (indexed by the proportion of time for which attention is captured by the processing component of the complex memory span task) and processing complexity (also influencing cognitive load) jointly determine complex memory span. In other words, cognitive load constrains complex memory span where cognitive load is defined by the ratio between processing time and the total time allowed to perform the processing component. Given Barrouillet and colleagues’ conception of attentional switching in complex memory span performance, it is to be noted that developmental data explicitly measuring children’s attentional focus switching skills is still lacking.

*Sustained attentional focus*. An attention control ability that is indispensable for adequate performance on many cognitive tasks is sustained attentional focus. Sustained attention is the ability to maintain one’s attentional focus over a period of time on a given task. It is well established that children’s sustained attentional focus improves with age (Gomes et al., 2000; Lin, Hsiao, & Chen 1999; Richards, 2004), and developmental improvement in sustained attentional focus has been related to the development of other cognitive abilities. Sustained attentional focus for example is important to early learning skills in children. Higher sustained attention abilities are positively associated with higher IQ, better language abilities and academic skills (Hanson & Montgomery, 2002; Jones et al., 2003; Manly et al., 2001; Noterdaeme et al., 2000; Spaulding et al., 2008). Because sustained attention is important to the development and functioning of various cognitive skills, it is logical to expect that sustained attention focus should have a similar role in working memory. For example, in complex memory span tasks used to measure working
memory performance, sustained attentional focus could play a vital role given the nature of the task. In a complex memory span task, participants are required to remember items for later recall while the to-be-remembered items are interleaved with processing functions. Such time-based storage across multiple trials of processing functions to be carried out requires sustained or vigilant attention over a period of time. Rapidly and accurately accessing items within and out of the focus of attention in working memory requires sustained attention skills. This is because vigilance is required while carrying out multiple switching trials. In a complex memory span task, during processing, storage items go out of the focus of attention and need to be retrieved into the focus later during recall. Vigilance especially becomes crucial to performance in children in whom this skill is still developing. While studies have defined the role of attention control and switching in complex memory span performance (Cowan et al., 2005; Kane et al., 2001; Lepine, Bernardin, et al., 2005; Unsworth & Engle, 2008) the role of sustained attentional focus has not been systematically explored.

Summary of Conceptualizations of Executive Attention Skills Within Working Memory

In summary, conceptualizations of executive attention skills within working memory have so far included the role of attentional capacity and control (multiple as well as single executive control functions) as constraints. It is critical to note that the role of controlled attention (specifically inhibition) in working memory has been predominantly studied in adults (e.g., Friedman & Miyake, 2004; Kane et al., 2001). Though Baddeley, Cowan, Barrouillet, and their colleagues (Baddeley, 1990, 2000; Barrouillet et al., 2009; Cowan et al., 2005) have discussed attentional capacity, executive control and focus
switching with reference to children’s complex memory span, their studies do not explicitly measure specific attention control mechanisms as predictors of complex memory span. That is, the role of attention in their studies has been inferred from task manipulations to the cognitive load of complex memory span tasks. The few other developmental studies that exist have broadly explored Baddeley’s conception of central executive functions (St Claire-Thompson & Gathercole, 2006; Zoelch et al., 2005). Finally, typically developing children’s attentional focus switching skills, inhibition, and sustained attention skills as they relate to working memory remain unexplored. There appears to be a developmental association between various attention mechanisms and cognitive functioning in children. The literature also clearly suggests an association between attention and complex memory span performance. However, from a developmental memory perspective, explicit measurement of attention control mechanisms of working memory clearly needs further exploration.

Research Examining the Effects of Multiple Working Memory Mechanisms on Children’s Complex Memory Span

Investigators have begun only recently to examine the contribution of a combination of factors to children’s complex memory span performance. To our knowledge, only two published studies have examined this issue (Bayliss et al., 2003, 2005); these studies only include processing speed and storage.

Bayliss and colleagues examined the influence of storage and processing speed (efficiency) on the complex memory span of 120 typically developing children between 6 and 10 years of age. They also assessed the domain-specificity of storage by including
verbal and visuospatial complex memory span tasks. In both tasks, the children were presented with the same display screen consisting of nine different colored squares. Each square contained a single digit (i.e., 1-9) in its center. In the verbal complex memory span task, the children were required to make an association between an auditorily presented object name (grass) and the color typically associated with the object (green). Immediately following hearing the object name, the children were asked to locate the square corresponding to the color of the object. Selecting the appropriate colored object represented the processing component of the task. The children were also asked to remember the digit located in the center of each square. At the end of each trial, the children recalled as many digits as possible (i.e. storage component of task). In the visuospatial complex memory span task, children were required to scan the display to locate a target square that was differentiated from the other squares by a combination of size and type of square. The children were then required to remember the location of the square. Across both tasks each processing and storage episode was presented for a fixed time window of 5500 ms, thereby controlling the time of the retention interval (Towse et al., 1998). In addition to the complex memory span tasks the children completed separate storage tasks to assess verbal storage (digit span) and visuospatial storage (corsi span). Verbal and visuospatial processing speed/efficiency was also measured using the same complex memory span tasks except that the tasks did not include the storage component. Processing speed was also assessed using two other tasks. Results of hierarchical linear regression and structural equation modeling analyses revealed that age-related changes in both processing speed (efficiency) and storage contributed to the developmental
improvement in children’s complex memory span. Bayliss et al. (2003, 2005) interpreted their results to suggest that explanatory models of children’s complex memory span performance must include both processing speed and storage.

In a preliminary study (Magimairaj et al., 2009), we examined the contribution of three mechanisms of working memory: short-term memory storage, processing speed and attentional allocation to children’s complex memory span performance. Assessing storage and processing speed served to replicate the approach taken by Bayliss et al. (2003, 2005). Inclusion of a measure of attentional allocation served to extend these investigators’ work. One task was used per variable. Tasks used were: digit span (short-term memory storage), Woodcock Johnson auditory working memory subtest (attentional allocation), an auditory-visual reaction time task (basic processing speed), and a complex listening span task. The digit span task involved serial order recall of lists of digits increasing in list length from 2 to 7 digits with three trials at each list length. The dependent variable on this measure was the longest list length with accurate recall. While the Woodcock Johnson auditory working memory subtest (Woodcock, McGrew, & Mather, 2001) was similar in structure to the digit span test, it differed in the nature of the stimuli. Stimuli consisted of a random combination of words and numbers. Children were required to recall the lists in serial order starting with words first followed by the numbers. The dependent variable was the longest list length with perfect recall. The basic processing speed measure was a simple speed task requiring touching the correct color on the computer touch screen quickly in response to listening to the name of a color word.
Three primary colors (red, blue, green, yellow) of a single shape (circle, square, or triangle) were displayed on the screen.

In the complex listening span task used in our study children listened to sets of simple sentences ranging from 2 to 6 sentences. After each sentence, children were required to give a yes/no response on the touch screen based on the truth value/plausibility of the sentence; at the end of each set, children were required to recall all the sentence-final words in any order. Complex memory span was defined as the total percent words accurately recalled across all 20 sentences. Results of this preliminary investigation, in agreement with the Bayliss studies, revealed that both storage and processing speed contributed unique variance to complex memory span. Although attention allocation correlated with the other measures (such as storage and complex memory span) it failed to contribute any unique variance to complex memory span above and beyond that contributed by age and storage.

In spite of methodological differences between our study and the Bayliss studies, all studies were in agreement regarding the robustness of storage and processing speed as predictors of complex memory span. Further exploration of the contributions of processing speed is warranted to clearly delineate the nature and number of speed tasks to be used. Finally, more robust measures of attention need to be used in order to determine the contribution of attentional mechanisms to complex memory span. The Woodcock Johnson auditory working memory subtest used in the preliminary study could have possibly been a weak measure of attentional allocation, because it predominantly reflected storage, i.e., shared a large amount of variance with short-term memory storage.
This was probably one of the reasons (in addition to using a single measure instead of multiple measures to index attentional allocation) why attentional allocation failed to contribute unique variance to complex memory span.

Given what we know about the development of attention and its relation to other cognitive abilities, we speculated that children’s attention should be important to working memory. Developmental models of working memory as well as studies from the adult literature affirm this association. However, specific attentional mechanisms need further exploration to more clearly explain aspects of attention within working memory. The current project focused on the role of two attention control mechanisms in children’s complex memory span. However, investigating attention posed two related challenges concerning measurement. Given the goal of the project, the first challenge concerned minimizing the effects of extraneous variables such as perceptual, motor, and/or language that could negatively affect “basic” attentional performance (Manly et al., 2001). The second challenge we expected was that, the tasks allow children to perform with some measure of success, while demonstrating age sensitivity and reliability, and without yielding floor or ceiling effects.

In the current study, we examined the role of two attention control mechanisms in children’s complex memory span performance: sustained attentional focus and attentional focus switching. We adopted a theory-neutral view of attentional mechanisms in their prediction of complex memory span. That is, we maintained that these attentional mechanisms represent constructs, which could either (a) be considered components of the central executive of Baddeley’s multi-component model of working memory or (b)
reflect the viewpoint of Engle et al. or Barrouillet et al. where attentional capacity and/or attention control is predicted to be critical to working memory performance. Hence, in the present study, sustained attentional focus and attentional focus switching were hypothesized to be predictors of complex memory span performance. If both constructs prove to be significant predictors, future studies may wish to examine the potential theory-specific role of these constructs. Future studies may also wish to examine the role of controlled attention along with short-term memory storage and processing speed as predictors of complex memory span.

Motivations for the Present Study

The developmental literature makes clear that children’s complex memory span increases with age and that it is influenced by processing speed, short-term memory storage, and attentional capacity and control. Studies in the adult literature provide greater and clearer evidence of how attentional capacity and attention control constrain working memory. Because there are few empirical studies that explicitly address the issue of what specific attentional mechanisms operate to constrain children’s complex memory span performance, the current project was undertaken. In the first phase of our research, we investigated the contribution of attentional allocation to complex memory span performance in children. The present study extended this work by examining multiple attentional control mechanisms in greater depth. This study expected to provide important information about two potential attention control mechanisms in school-age children’s complex memory span performance: sustained attentional focus and attentional focus switching.
Children in the age range of 7-11 were the focus of this study. This age range of children was of interest because (a) working memory skills are known to improve significantly during this developmental period (Gathercole, 1999), (b) it has been suggested in the literature that similar to marked developmental improvements in verbal rehearsal skills at age 7, attentional mechanisms such as attention control are also expected to be significantly improving at this age (Barrouillet et al., 2009; Morris, 1996; Pearson & Lane, 1991; Portrat et al., 2009; Zoelch et al., 2005), and (c) pilot data and previous work in our lab have shown that children younger than 7 have trouble performing on some of the experimental tasks.

Sustained attentional focus was indexed by children’s performance on two continuous performance tasks, one auditory and one visual. Attentional focus switching was indexed by two attentional focus switching tasks (based on the Garavan paradigm), one each in the auditory and visual input domains. Complex memory span was measured using a revised version of the listening span task used in our preliminary studies (Magimairaj et al., 2009) and a computerized adaptation of the counting recall task from the Working Memory Test Battery for Children (Pickering & Gathercole, 2001).

This project employed a robust psychometric approach. A psychometric approach allows researchers to build and test a model(s) describing the relationship between predictor and outcome variables (Swets, Desmet, Hambrick, & Ferreira, 2007). Such an approach has three important features. The first is the use of two or more measures to represent each mental construct of interest. Multiple measures permit the use of factor analytic techniques to isolate the construct-relevant variance common to the different
measures. A second feature is the use of larger samples. Larger samples provide power and stability of the derived factors and allow researchers to determine whether the predictor and outcome variables are linear across the full range of scores within the sample(s). Third, researchers are able to use such procedures as General Linear Modeling to assess the relative importance of various predictors to the outcome variable.

In the current study, two measures, one auditory and one visual indexed each attention construct. Complex memory span was likewise indexed by an auditory and a visual measure. Sixty-one children (7 to 11 years of age) participated in the study. The combination of multiple measures and a moderately large sample permitted us to conduct General Linear Modeling procedures to determine how much variance in children’s complex memory span each of the attention constructs accounted for.

**Specific Aims and Predictions**

The specific aim of this project was to evaluate the unique contribution of sustained attentional focus and attentional focus switching in predicting 7- to 11-year-old children’s complex memory span. Two variables that were controlled for were age and speech production rate. Age and speech rate were adjusted for to obtain a purer estimate of the relation between the memory variables uninfluenced by other age-related variables (for example, motor speed). It was expected (based on pilot observations) that older children were faster at articulating their count updates when compared to younger children. Hence, to isolate the retrieval time required to bring items into and out of the focus of attention (which reflects the attentional switching mechanism) from the overall performance measure (which includes articulation of the counts as children are updating
them and moving to the next stimuli), a measure of speech rate was included and used as a control during data analysis.

It was predicted that both sustained attentional focus and attentional focus switching would jointly contribute to significant variance in complex memory span performance, after adjusting for age and speech rate. It was also predicted that attentional focus switching would emerge as the more significant predictor given its hypothesized role in existing working memory models (Barrouillet et al., 2009).
CHAPTER 3: METHOD

Participants

Sixty-one children participated in the present study that examined the contribution of sustained attentional focus and the accuracy and speed of attentional focus switching to 7- to 11-year-old typically developing children’s complex memory span performance. This particular age range was selected because children’s working memory skills are known to improve steeply throughout this range. Recent studies also suggest that, similar to the developmental shift in verbal rehearsal abilities at this age, children also commence using attentional focus switching skills consistently around this age (Portrat et al., 2009). In addition, pilot work in our lab suggests that children younger than 7 do not show consistent and reliable performance on some of the memory tasks to be used here. A moderately large N was required for adequate power given the predicted effect size and the nature of the statistical analyses that were used to address the research question. Finally, an attempt was made to recruit comparable numbers of boys and girls at ages 7, 8, 9, 10, and 11. The sample was comprised of 34 girls and 27 boys (\( M_{\text{Age}} = 9.5 \text{ years}; \ SD = 1.27; \ Range = 7-11.6 \text{ years} \)) and was balanced in the number of younger and older children. There were 33 younger children (7- to 9.5-year-olds) and 28 older children (9.5- to 11-year-olds).

All of the children demonstrated at least normal-range nonverbal IQ (\( \geq 85 \)) on the Test of Nonverbal Intelligence-3 (TONI; Brown, Sherbenou, & Johnsen, 1997) and normal-range hearing sensitivity as determined by audiometric pure tone screening at 25 dB HL (ANSI, 1990) for 500 Hz, 1 kHz, 2 kHz, and 4 kHz. The children also
demonstrated normal or corrected vision. Children presented no history of language problems, academic difficulties, neurological impairment, psychological/emotional disturbance, or diagnosed attention deficit disorder based on parent(s) report on a developmental questionnaire (see Appendix A).

The children also met the following language criteria. All children were fluent speakers of English as determined from language screening. Children obtained a receptive language score and an expressive language score at or above -1 SD from the mean on two subtests of the *Clinical Evaluation of Language Fundamentals* (CELF-4; Semel, Wiig, & Secord, 2003); concepts and following directions and recalling sentences. Children also obtained a score that was -1 SD or higher on the *Test for Reception of Grammar-2* (TROG-2; Bishop, 2003), a syntax-specific receptive measure, and the *Peabody Picture Vocabulary Test -3* (PPVT; Dunn & Dunn, 1997), an index of single word receptive vocabulary knowledge. Table 1 displays the children’s standard scores on all measures.
Table 1

*Descriptive Statistics for all Language Screening Measures (N = 61)*

<table>
<thead>
<tr>
<th>Measure</th>
<th>M</th>
<th>SD</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>TONI-3</td>
<td>116.74</td>
<td>14.33</td>
<td>90 – 150</td>
</tr>
<tr>
<td>PPVT-3</td>
<td>112.69</td>
<td>13.58</td>
<td>87 – 157</td>
</tr>
<tr>
<td>TROG-2</td>
<td>112.10</td>
<td>7.70</td>
<td>88 – 123</td>
</tr>
<tr>
<td>*Oral Directions</td>
<td>12.90</td>
<td>1.88</td>
<td>6 – 17</td>
</tr>
<tr>
<td>*Recalling Sentences</td>
<td>12.74</td>
<td>2.46</td>
<td>5 – 18</td>
</tr>
</tbody>
</table>

*Note. TONI-Test of Non-Verbal Intelligence, PPVT-Peabody Picture Vocabulary Test, TROG-Test for Reception of Grammar, *subtests of the CELF-Clinical Evaluation of Language Fundamentals.*

Recruitment Procedures

Children were recruited through a variety of means, including Ohio University website announcements and flyers posted at local churches and the Athens Community Center. Parents/caregivers who were interested in the study, passed a preliminary phone screening for eligibility, and gave their permission using a consent form and procedure approved by Ohio University’s Institutional Review Board were able to commence the study. Children received a toy after each visit and parents received a report of the child’s language test findings as well as compensation of $10 per visit.
General Testing Procedures

All children were seen individually at the Developmental Psycholinguistics Lab in Grover Center. Children completed three to four testing sessions, each lasting about an hour with adequate rest breaks. During the school year, children were scheduled after school hours and on the weekends. Scheduling was flexible during the day in the summer. Three different counterbalanced orders of the seven experimental tasks were created. An equal number of children completed each order. All computerized tasks were created and delivered using E-Prime software (Psychology Software Tools, Inc.).

Experimental Tasks

Seven experimental tasks were administered to all the children. Two of the tasks assessed sustained attentional focus, two assessed attentional focus switching, and two assessed complex memory span. One task measured children’s speech production rate. Table 2 lists all experimental tasks, variables examined within each task, and the outcome for each construct used in the model for addressing the primary research question.

Sustained Attentional Focus

Children’s ability to sustain attentional focus was assessed using two subtests of the *Gordon Diagnostic System*, a commercially available continuous performance test (Gordon, McClure, & Aylward, 1996). The *Gordon Diagnostic System* consists of a battery of measures used to assess a range of children’s and adolescents’ sustained attention and impulse control. This device is portable and electronic, and has been frequently and successfully used as a valid measure of children’s sustained attentional focus in both clinical and experimental settings (Gordon et al., 1996; Mayes, Calhoun, &
Auditory Vigilance Task

Task design and stimuli. Auditory stimuli consisted of a series of single digit numbers randomly selected between 1 and 9. The order was predetermined by the system and each number always appeared for .2 seconds. Presentation interval was defined as the time from when a number first appeared to the initial presentation of the next number. The presentation interval was set at 1 second and consequently the blank phase between two presentations was .8 seconds.

Task procedures. Children listened to a man saying a series of single digit numbers and pressed a button as soon as and every time the unique number sequence “1, 9” was heard (see Appendix B for test instructions). Demonstration and practice trials using live voice presentation were carried out before the test trials. If a child did not hit the button accurately three times during practice, live voice presentation was repeated with the examiner assisting the child by placing his/her hand over the child’s hand and helping the child respond. Once the child independently passed practice (hit button accurately three times) the task proceeded to the test trials. Test trials were presented under headphones. Loudness levels under headphones were adjusted to each child’s comfortable listening level prior to commencement of test trials.

Dependent variable. The Gordon Diagnostic System automatically records the total number of hits, misses, and false alarms. The primary dependent variable was the
total number of hits (number of times the child correctly presses the button upon hearing “1, 9”). The hits, misses, and false alarms were then manually recorded onto the child’s score sheet.

Visual Vigilance Task

Task design and stimuli. Visual stimuli consisted of a series of single digit numbers randomly selected between 1 and 9 and presented on an liquid crystal display screen. The order was predetermined by the system and each number always appeared for .2 seconds. Presentation interval was defined as the time from when a number first appeared to the initial presentation of the next number. The presentation interval was set at 1 second and consequently the blank phase between two presentations was .8 seconds.

Task procedures. Each child was given the same set of test instructions (see Appendix C). Children saw a series of single digit numbers and pressed a button as soon as and every time the unique number sequence “1, 9” appeared. Demonstration and practice trials using live voice presentation were carried out before the test trials. If a child did not hit the button accurately three times during practice, live voice presentation was repeated with the examiner assisting the child by placing his/her hand over the child’s hand and helping the child respond. Once the child independently passed practice (hit button accurately three times) the task proceeded to the test trials.

Dependent variable. The Gordon Diagnostic System automatically records the total number of hits, misses, and false alarms. The primary dependent variable was the total number of hits (number of times the child correctly pressed the button upon seeing
“1, 9”). The hits, misses, and false alarms were manually recorded onto the child’s score sheet.

**Attentional Focus Switching**

Attentional focus switching was indexed by two tasks, one each in the auditory and visual domains. The developmental memory and attention literatures lack focus switching paradigms. For this reason, two tasks were developed for the current project. The paradigm was an adapted version of the Garavan paradigm (Garavan, 1998; Garavan et al., 2000; Unsworth & Engle, 2008), which involved continuous count-updating. Participants were presented trials of two similar yet highly discriminable stimuli (e.g., big square/small square). Each trial contained a different number of each stimulus type. Participants were asked to keep a running count of each stimulus encountered and at the end of the trial report the total number of each stimulus type presented. Performance on such a task presumably relates to solving a complex memory span task because complex memory span tasks entail switching the focus of attention between storage and processing elements of the task. That is, at any one time the focus of attention either includes processing or the stored items to be recalled. Similarly, attentional switching costs are invoked when switching between updating counts of two distinct stimuli in contrast to updating the count of a single stimulus that is repeated. Such switching costs were a reflection of the attentional switching skills of the children with lower costs corresponding to better or more efficient switching performance.
Auditory Attentional Focus Switching

Task design and stimuli. Auditory stimuli consisted of a 500 ms, 250 Hz tone and a 500 ms 4000 Hz tone. These frequencies were found to be easily discriminated by the children of this age range. The specifications selected were based on pilot data tested using a range of durations (250 ms, 500 ms, 750 ms, and 1000 ms) and frequencies (250 Hz/500 Hz, 2000 Hz/4000 Hz). The most comfortable duration for children to perform adequately on this task was 500 ms. A total of 30 test trials were included. Each trial sequence consisted of 7-11 tones with six trials each at each sequence length. Thus, the total number of stimuli was 270 tones. The order of appearance of tones followed a predetermined order within a trial. A random sequence length was used across trials. The entire task consisted of six blocks of five trials each. The task was divided into two experiments each consisting of three blocks.

Presentations were switch or non-switch in nature. In a non-switch presentation, the tone presented was the same in pitch as the previous tone; in a switch presentation, the tone presented was different from the previous tone (i.e., low followed by high pitch and vice versa). Presentation interval was defined as the time from when a tone first appeared to the initial presentation of the next tone. Approximately one third (108) of the total presentations (270) were switch presentations while the remaining two thirds were non-switch (162). Among the 30 trials, 15 included high frequency switches (where 50% of the presentations within a trial were switch presentations) while the other half included low frequency switches (where 25% of the presentations within a trial were switch presentations).
Task procedures. Each child was given the same set of test instructions (see Appendix D). Each child was asked to keep count of each type of stimulus that was heard one at a time. Each stimulus appeared only when the child pressed the space bar for the next one. Children were asked to be as accurate and fast as possible on the task. The task commenced with a fixation point on the screen for 150, 300, or 600 ms (random for each trial) followed by one of the two tones (e.g., Unsworth & Engle, 2008). After the child updated the count of the tone overtly (as follows below), he/she pressed the space bar for the next presentation. On pressing the space bar, the fixation point appeared on the screen again followed by the next tone. After each presentation, the child updated both the counts (i.e., high and low tones). For example, if the child already heard two high frequency tones and three low frequency tones and then heard a low frequency tone, he/she would say “two high, four low.”

At the end of each trial, a recall cue appeared in the form of the computer screen turning green. A report in any order was acceptable (i.e., the child was allowed to recall the total count of each tone in whichever order he/she preferred: high, low or low, high). In total three practice trials were used: one each at sequence lengths 7, 8, and 9 in that order. Demonstration and practice trials were repeated if the child did not perform correctly on at least two of the three trials. This was indicative of whether the child understood task instructions appropriately.

Dependent variable. Two dependent measures were obtained. The first dependent measure was the accuracy of the counts. The child’s responses were recorded verbatim on to a score sheet trial by trial. Because the trials were constructed in a predetermined
order, the examiner was able to compare the obtained responses to the actual counts during data analysis. A score of 1 was given for every trial where both counts (high and low tone) were recalled correctly. If only one of the two counts was correct, the trial was given a score of .5; if neither count was correct, the trial was given a score of 0. The total number of trials was 30; therefore, the maximum possible score was 30. Accuracy on high frequency and low frequency switch trials were computed separately. Individual count accuracy for each type of tone was also computed to make sure identification of one type of tone was not significantly higher than the other (which may be indicative of an advantage of one stimulus quality over another). A second outcome measure was the mean reaction time on each of two categories of stimuli presentations: switch and non-switch presentations. Reaction time was defined as the time taken to update each count, i.e., from one stimulus onset till the space bar press for the next presentation. Difference between the mean reaction time from switch presentations and mean reaction time from non-switch presentations reflected switch cost and the mean switch reaction time reflected speed of focus switching.

*Visual Attentional Focus Switching*

*Task design and stimuli.* Visual stimuli consisted of two clearly distinguishable squares: a big red square vs. a small red square (adapted from Unsworth and Engle, 2008). A total of 30 test trials were included. Each trial sequence consisted of 7-11 squares with six trials each at each sequence length. Thus, the total number of stimuli was 270 squares. The order of appearance of squares followed a predetermined order within a trial. Across trials a random sequence length was used. The entire task consisted of six
blocks of five trials each. The task was divided into two experiments each consisting of three blocks.

Presentations were switch or non-switch in nature. In a non-switch presentation, the square presented was the same as the previous square; in a switch presentation, the square presented was different from the previous square (i.e., big followed by small square and vice versa). Presentation interval was defined as the time from when a square first appeared to the initial presentation of the next square. Approximately one third (108) of the total presentations (270) were switch presentations while the remaining two thirds were non-switch (162). Among the 30 trials, 15 included high frequency switches (where 50% of the presentations within a trial were switch presentations) while the other half included low frequency switches (where 25% of the presentations within a trial were switch presentations).

Task procedures. Each child was given the same set of test instructions (see Appendix E). Each child was asked to keep count of each type of stimulus that was seen one at a time. Each stimulus appeared only when the child pressed the space bar for the next one. Children were asked to be as accurate and fast as possible on the task. The task commenced with a fixation point (“+”) on the screen for 150, 300, or 600 ms (random for each trial) followed by one of the two squares (e.g., Unsworth & Engle, 2008). Once the child updated the count of the squares overtly (as follows below), he/she pressed the space bar for the next presentation. After pressing the space bar, the fixation point appeared on the screen again followed by the next square. After each presentation, the child updated both the counts (i.e., big and small squares). For example, if the child
already saw two big squares and three small squares and is next presented with a small square he/she would say “two big, four small”.

At the end of each trial, a recall cue appeared in the form of the computer screen turning green. A report in any order was acceptable (i.e., child was allowed to recall the total count of each type of square in whichever order he/she preferred: small, big or big, small). In total three practice trials were used one each at sequence lengths 7, 8, and 9 in that order. Demonstration and practice trials were repeated if the child did not perform correctly on at least two out of three trials. This was indicative of whether the child understood task instructions appropriately.

*Dependent variable.* Two dependent measures were obtained. The first was the accuracy of the counts. The child’s responses were recorded verbatim on to a score sheet trial by trial. Since the trials were constructed in a predetermined order the examiner was able to compare the obtained responses to the actual counts during data analysis. A score of 1 was given for every trial where with both counts (big and small square) were recalled correctly. If only one of the two counts was correct, the trial was given a score of .5; if neither count was correct, the trial was given a score of 0. The total number of trials was 30; therefore, the maximum possible score was 30. Accuracy on high frequency and low frequency switch trials were computed separately. Individual count accuracy for each type of square was also computed to make sure identification of one type of square was not significantly higher than the other (which may be indicative of an advantage of one stimulus quality over another). A second outcome measure was the mean reaction time on each of two categories of stimuli presentation: switch and non-switch presentations.
Reaction time was defined as the time taken to update each count, i.e., from the onset of one stimulus till the space bar press for the next presentation. Difference between the mean reaction time from switch presentations and mean reaction time from non-switch presentations reflected switch cost and the mean switch reaction time reflected speed of focus switching.

Pilot Testing

Because both the auditory and visual attentional focus switching tasks were developed based on the adult literature, both tasks were piloted on five 7- to 8-year-olds and five 10- to 11-year-olds to determine their suitability for children. Two versions of each task were used. One version included sequences varying from three to seven items and the other included sequences varying from 7 to 11 items. Both versions were administered to all the children. The reason for using two versions was to determine ceiling and floor effects, and, in turn, the sequence length that was suitable for administration to this age group. The results from each version of the task, for each age group, were examined for mean score, standard deviation, and range. Of interest was whether (a) the children were able to perform the task with relative consistency, (b) floor and ceiling effects were avoided, (c) the tasks appeared to be age sensitive, and (d) task items and their features were appropriate for the children. Additionally, observations about the understandability of the instructions and the children’s general task demeanor were noted. Based on pilot testing, the sequence length of 7 to 11 items was selected for use in the main study for both the auditory and visual focus switching tasks. Sequence lengths of 7-11 appeared to be age sensitive without causing floor or ceiling effects.
Three to seven items proved to be very easy and thus led to ceiling effects on the pilot for all children. Children performed the tasks with good consistency and followed the instructions easily. Secondary to the sequence length evaluation, for the auditory focus switching task, a range of durations (250 ms, 500 ms, 750 ms, and 1000 ms) and frequencies (250 Hz/500 Hz, 2000 Hz/4000 Hz) for the tonal stimuli were piloted. Based on this pilot, tones for the main study were selected to be 500 ms in duration and of the frequencies 250 Hz and 4000 Hz for the low and high tone respectively. The 500 ms duration was the most comfortable for the children and 250 Hz and 4000 Hz were most clearly distinguishable frequencies in this context causing no confusions in labeling them consistently.

Speech Production Rate

Speech production rate was measured by a simple task requiring children to produce a series of words that mirrored the production requirements in the auditory and visual focus switching tasks. Speech rate as captured by this independent measure was controlled for during analysis of the attention switching tasks. This was done to isolate the retrieval time taken in the attention-switching task as reflected by the reaction time measure (i.e., reaction time for switch and non-switch trials).

Task Design and Stimuli

The task consisted of two lists of words that the children were first familiarized with. One list included the numbers and words 1 to 10 “big” and 1 to 10 “small” and the second list included 1 to 10 “low” and 1 to 10 “high” (see Appendix F for task stimuli and instructions). This task mirrored the switching task in terms of the actual words the
children produce during the original task but it did not have any “retrieval” demands as in the switching tasks.

Task Procedures

Each child was given the same set of test instructions. The children were required to say the words on each list as quickly as they could into the microphone. Children’s production was recorded using Adobe Audition software (Adobe Systems Inc.).

Dependent Variable

Because the total number of syllables on each list was 42, the rate of speech production (outcome variable) was determined by dividing 42 by the total time taken on each list.

Complex Memory Span

Procedures for recording, generating, and editing the verbal stimuli making up the listening span task were as follows. A male speaker with a neutral Midwest (U.S.) dialect read the stimuli (in an isolated acoustic booth) using a high quality microphone connected to a Dell computer. The sentences for the listening span task were read at a normal rate (~ 4.4 syllables/sec; Ellis Weismer & Hesketh, 1993) and with normal prosodic variation. All stimuli were digitized at 22.5 kHz, low-pass filtered (10 kHz), and normalized for intensity using Cool Edit Pro-2. Each wave file was then edited to eliminate any noise at the beginning or end of the file.

Listening Span Task

This measure of complex memory span was a revised version of our original listening span task (Magimairaj et al., 2009). Children were presented sets of sentences
and asked to (a) comprehend the meaning of each sentence and (b) remember a digit presented immediately after the last word of each sentence.

Task design and stimuli. The task consisted of simple sentences, which were 8 words in length. The intent of the task was to present children sentences that closely approximate “everyday” language input. The sentences in the present study included a range of simple structures appropriate to the comprehension of 7-year-old children (Booth, MacWhinney, & Harasaki, 2000; Dick, Wulfeck, Krupa-Kwiatkowski, & Bates, 2004; MacWhinney, 1982), including subject-verb-object sentences (e.g., Most big birds can eat a little ship) and sentences containing a conjoined verb phrase (e.g., Birds fly in the sky using their nose) or conjoined adjectival phrase (e.g., The lady found a puppy that was furry). All of the words in the sentences were high familiarity words in children (Cortese & Khanna, 2008; Moe, Hopkins, & Rush, 1982). Because the present task is part of a larger research program designed to examine the interaction of working memory and language processing in children with specific language impairment, controlling word familiarity was deemed important. The task consisted of a total of 40 sentences with set size presented in a predetermined order across two-sentence sets to six-sentence sets (order of presentation by set size: 4, 3, 6, 2, 5). There were two trials at each set size.

Half of the sentences were constructed to require a “Yes” (true) response (i.e., sentence had truth value) and half the sentences required a “No” (false) response (i.e., sentence had no truth value). For the “No” sentence, the sentence was false because of a semantic violation (e.g., Dogs like sleeping in clouds that are soft, The cat saw the house that was hopping).
Following each Yes/No response, a monosyllabic single digit number was heard which was to be remembered for later recall. In a conventional listening span task, the last word of the sentence has been the item to be remembered for later recall. However, investigators have observed that individual differences could influence recall of sentence final elements as subjects could use the gist of the sentence to guess or predict the word (Conway et al., 2005). Researchers thus recommend that the element that is interleaved between processing phases for later recall be unrelated to the sentence. Hence, a single digit number (except 0, 3, and 7) was used after each sentence for later recall. This was with the aim of keeping all recall digits monosyllabic and avoiding the cluster /thr/ as in “three” which could be difficult for children with language impairment on whom this experiment may be used in the future as part of a larger research program. Finally, no sentence-final number repeated within a set.

Task procedures. The child sat in front of the computer monitor, resting his/her elbow on a soft pad and was instructed to place his/her middle finger tips of his/her dominant hand on the “+” that appeared in the middle of the screen. The child was told that he/she would hear a man saying some groups of sentences and he/she would need to do two things: respond to the truth value of each sentence and then at the end of the set recall as many of the sentence-final numbers in that sentence set as he/she could remember.

Each sentence was delivered binaurally under headphones at a comfortable listening level (determined by the child). The child was told to touch the word “Yes” on the touch screen if the sentence reflected an event that could happen in real life, or “No”
if the sentence reflected an event that could not occur in real life. The child was instructed to make his/her response as quickly as possible. However, the child was instructed to wait until the end of the sentence to make his/her response to make sure he/she knew whether the sentence was true or not. In addition to assessing response accuracy, the time taken to respond was measured. An inaudible timing pulse was located at the beginning of the sentence and gated on the computer’s internal clock. The computer automatically recorded response accuracy. Processing time was calculated as the difference between sentence offset and when the child made his/her response. Any response occurring before sentence offset was scored a false alarm and failure to respond was scored a miss.

The task was administered in an experimenter-paced fashion. That is, after each sentence was responded to with a Yes/No the random number to be remembered was heard. Immediately following the number the experimenter presented the next sentence. Presenting each sentence immediately after one other was intended to prevent the child from rehearsing the numbers between sentence trials¹. Finally, after the entire block of sentences and to-be-remembered numbers was delivered, the computer screen turned green cueing the child to recall the sentence-final numbers. The child was to recall the numbers in serial order of presentation, as is convention in the memory literature. List length was not incremental from two- to six-sentence sets as has been conventionally used. Instead the task began with the four-sentence set, followed by the following order

¹ While stimulus presentations were experimenter-paced in this study based on the recommendations by Conway et al., (2005), recent studies in the memory literature suggest that better time control of the processing episode is obtained by fixing the total processing time allowed (Barrouillet et al., 2009).
of list lengths 3, 6, 2, 5. This was to avoid children’s expectancies that the task would get incrementally harder which could likely influence their motivation (Conway et al., 2005).

Dependent variable. The primary dependent variable was percent sentences for which the child correctly recalled the sentence-final numbers. This was based on the partial credit-unit scoring which has been demonstrated to be a more robust measure of complex memory span than absolute span scores (Conway et al., 2005). In such a scoring method, credit is given to every correct trial unlike the absolute span score, which is equal to the largest set size with perfect recall. According to Conway et al., the limited range (2-6) of absolute span scores reduces variability of test scores thereby reducing its sensitivity. Comprehension accuracy (though not the primary variable of interest) was also examined to ensure all sentences were age appropriate and comprehended equally well by the subset of children studied.

Counting Span Task

The computerized adaptation of the counting recall subtest from the Working Memory Test Battery for Children (Pickering & Gathercole, 2001) was used in the present study. Children were asked to count arrays of dots presented on the screen, one array at a time. After a set of arrays was counted the child recalled the total count from each array in serial order, which determined the counting span of the child.

Task design and stimuli. Stimuli consisted of arrays of dots with each array ranging anywhere between four to seven dots. The dots were red in color and appeared on a white background. The diameter of each dot was 85 px. Before each array was presented a fixation point “+” appeared on the screen for 100 ms. Each block of trials
consisted of arrays. Arrays increased in length from one to six arrays to be counted. At each array length there were six trials. The selection of array length had a predetermined order.

*Task procedures.* The child sat in front of the computer screen and was instructed to point and count the dots aloud on each/successive array presented while at the same time keeping the total count of each array in memory for later recall. The recall cue was the screen turning green. The first block consisted of six trials of four arrays. After the child counted the dots on all four successive arrays the screen turned green and the child recalled the total from each array. The second block consisted of six trials of three arrays each. That is, the recall cue for reporting the counts appeared after three arrays. Similarly the task progressed in the order with blocks consisting of six trials of six, two, and five arrays each (mirroring the order on the listening span task). The experiment was discontinued if the child incorrectly recalled the totals on four trials at any given array length.

*Dependent variable.* For each trial recalled accurately and in the correct order the child was allotted a score of 1. Thus, the maximum possible correct trials score was 36 (credit was also given for array length 1 though it was not administered to any child unless there was a failure at length 2). Occasionally, if a child made an error in counting, the respective count reported by the child was regarded as the number to be recalled.

*Pilot testing.* Two versions of the counting span task were piloted over two separate sessions on five 7- to 8-yr-olds and five 10- to 11-yr-olds respectively. The counting span task has been used frequently in the developmental memory literature. On
the counting recall task by Pickering and Gathercole (2001), which was adapted for this study, image templates of dots at each array length are restricted to one or two images. Limited dot orientations could possibly lead to automatic visual recognition of the arrays rather than utilization of a counting process. This could render the processing too simple with very less cognitive load especially for the older children. Thus, children’s attentional resources may not be adequately switched away from storage or rehearsal in memory that is expected of a complex memory span task. Therefore, it was deemed necessary to create more variations of dot orientation for the four to seven dots that appeared in the task. More dot orientations were created and added to the original resulting in a total of five types of dot orientations for each array length. Thus, the second version of the task was exactly the same as the original task in terms of stimuli sequence, length, and task administration procedures except for the added image orientations. This pilot data helped determine if there were any significant differences between the two versions. Observations revealed that there were no significant differences between the two versions as long as the children pointed to individual dots and counted them out loud. This allowed us to decide that the original task’s image orientations were appropriate to be used for the present study.

Statistical Procedures

Preliminary Analyses

Data Trimming and Outlier Analyses

On each of the attentional focus switching tasks, one of the variables of interest was mean reaction time on switch and non-switch presentations. There were missing data
for one child on the auditory attentional focus switching task and for another child on the visual attentional focus switching task due to inability to complete the task.

Each child’s reaction time data for switch presentations and non-switch presentations on the auditory and the visual focus switching tasks were separated using a custom written MATLAB program (The MathWorks Inc.). This resulted in four separate reaction time data sets: auditory switch reaction time, auditory non-switch reaction time, visual switch reaction time, and visual non-switch reaction time. Reaction time data were trimmed in two phases based on the approach used by Friedman and Miyake (2004). First, for each reaction time data set, an arbitrary upper and a lower cut-off criterion was established by visual inspection. The criterion turned out to be the same for all the reaction time data sets (500 ms, 10,000 ms). In the first stage, all reaction times below 500 ms and above 10,000 ms were removed to prevent extreme reaction times from influencing the mean. Based on observational notes during testing these extreme reaction times generally occurred due to rare interruptions during testing. Less than 2% of the overall reaction times were eliminated from each data set in this first phase of trimming.

In the second phase means and standard deviations were computed for each child’s reaction time data obtained after trimming from the first phase. Outliers were defined as those reaction times that were farther than +/-3 SD from the respective series mean (Friedman & Miyake, 2004). Outliers were removed from the data set and were replaced with the recalculated mean of the remaining series to form the final valid data set. In the second phase of trimming less than 2% of the overall reaction times were removed from each data set.
Combining Scores Across Tasks

Two tasks were used for each of the two predictor constructs (sustained attentional focus, attentional focus switching) and the outcome (complex memory span). Outcome scores on each task were first saved as z scores. The z scores (i.e., one each obtained from the auditory and visual correlates of each task) were combined to obtain a unitary measure for each variable. Table 2 shows the final set of predictor variables used in the model: composite z (sustained attentional focus), composite z (overall accuracy of focus switching), and composite z (mean switch reaction time). Variables entered as controls were composite z (speech rate) and age. The dependent variable used was composite z (complex memory span).
Table 2

*Summary of all Experimental Tasks, Examined Variables, and Variables Used in the Model*

<table>
<thead>
<tr>
<th>Task</th>
<th>Examined Variables</th>
<th>Variables Used Towards Model Estimation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sustained Attentional Focus</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gordon-A</td>
<td>Total Hits</td>
<td>Composite z scores</td>
</tr>
<tr>
<td>Gordon-V</td>
<td>Total Hits</td>
<td>(Hits: Gordon-A + Gordon-V)</td>
</tr>
<tr>
<td><strong>Attentional Focus Switching</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A-Focus Switching</td>
<td>Overall accuracy</td>
<td>Composite z scores</td>
</tr>
<tr>
<td></td>
<td>Accuracy-High frequency trials</td>
<td>(Overall accuracy: A + V)</td>
</tr>
<tr>
<td></td>
<td>Accuracy-Low frequency trials</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Accuracy-High tones</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Accuracy-Low tones</td>
<td></td>
</tr>
<tr>
<td>V-Focus Switching</td>
<td>Overall accuracy</td>
<td>Composite z scores</td>
</tr>
<tr>
<td></td>
<td>Accuracy-High frequency trials</td>
<td>(Overall accuracy: A + V)</td>
</tr>
<tr>
<td></td>
<td>Accuracy-Low frequency trials</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Accuracy-Big Squares</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Accuracy-Small Squares</td>
<td></td>
</tr>
<tr>
<td>RT-A- FS</td>
<td>Mean Switch RT</td>
<td>Composite z scores</td>
</tr>
<tr>
<td></td>
<td>Mean Non-switch RT</td>
<td>(Mean Switch RT: A + V)</td>
</tr>
<tr>
<td>RT-V- FS</td>
<td>Mean Switch RT</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mean Non-switch RT</td>
<td></td>
</tr>
<tr>
<td><strong>Complex Memory Span</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Listening Span</td>
<td>Total trials with accurate word recall</td>
<td>Composite z scores</td>
</tr>
<tr>
<td></td>
<td>Comprehension accuracy</td>
<td>(Word recall: Lspan + Cspan)</td>
</tr>
<tr>
<td>Counting Span</td>
<td>Total trials with accurate count recall</td>
<td></td>
</tr>
</tbody>
</table>
Table 2: continued

<table>
<thead>
<tr>
<th>Speech Rate</th>
<th>Time taken to complete list A</th>
<th>Composite $z$ scores</th>
</tr>
</thead>
<tbody>
<tr>
<td>List A-high/low</td>
<td></td>
<td></td>
</tr>
<tr>
<td>List V-big/small</td>
<td>Time taken to complete list V</td>
<td>(Syllables/sec: List A + V)</td>
</tr>
</tbody>
</table>

*Note.* A-Auditory; V-Visual; FS-Focus Switching; RT-Reaction time; Lspan-Listening span; Cspan-Counting span.

**Diagnostics to Validate Model Assumptions**

Diagnostic measures such as histogram of errors, studentized residuals and Cook’s distance were used to examine for cases that might fall far from the regression equation. There were no outliers/influential cases. This indicated that the assumptions for the model were satisfied and the conclusions obtained from the model could be endorsed.

**Collinearity Statistics**

While there was some degree of relation among the predictor variables in the model, no multi-collinearity was expected. Collinearity statistics (Tolerance and Variance Inflation Factor) indicated that there was no multi-collinearity.

**Reliability Analysis**

Cronbach’s co-efficient of reliability was computed for each variable. Reliability on all the examined variables reflected item reliability on each task.

**Descriptive Statistics**

Descriptive statistics for all experimental tasks and age were conducted. Frequencies were conducted to report information on the distribution of the children by gender and age group (younger vs. older). Data for one child were excluded from the
auditory focus switching task accuracy variable because the child’s accuracy score was below 50%.

Primary Adjusted Analyses

Model Estimation

General Linear Modeling procedure was used to determine the contribution of each predictor to variance in complex memory span. All the predictor variables and controls were entered simultaneously for model estimation.

Secondary Analyses

Correlation Analysis

Correlations between all experimental measures and age were computed to report developmental trends on the constructs. Partial correlations between all experimental measures (controlling for age) were also computed.

Comparison of Means

Paired samples T-test was conducted to examine differences between (a) accuracy on high frequency vs. low frequency switch trials, (b) mean switch reaction time vs. mean non-switch reaction time, (c) accuracy on high tones vs. low tones, and (d) accuracy on big squares vs. small squares.
CHAPTER 4: RESULTS

Preliminary Analyses

Final descriptive statistics for the experimental tasks are summarized in Table 3. Average accuracy in performance on the predictors sustained attentional focus and attentional focus switching was 86.5% and 81% respectively, for children in the age range of 7 to 11 years. Average complex memory span performance was 64.5% and reflected the greater task demands as a superordinate construct in comparison to the predictors. Mean switch and non-switch reaction times on the focus switching tasks were also computed. Item reliability on all tasks was found to be good.
<table>
<thead>
<tr>
<th>Measure</th>
<th>M</th>
<th>SD</th>
<th>Range</th>
<th>Reliability*</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sustained Attentional Focus</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gordon-A (Hits)</td>
<td>36.54 (81%)</td>
<td>6.18</td>
<td>15 – 45</td>
<td>.85</td>
</tr>
<tr>
<td>Gordon-V (Hits)</td>
<td>41.31 (92%)</td>
<td>4.16</td>
<td>19 – 45</td>
<td>.85</td>
</tr>
<tr>
<td><strong>Attentional Focus Switching</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Auditory-FS (Overall accuracy)</td>
<td>23.61 (79%)</td>
<td>4.30</td>
<td>15 – 30</td>
<td>.83</td>
</tr>
<tr>
<td>Visual-FS (Overall accuracy)</td>
<td>24.89 (83%)</td>
<td>3.57</td>
<td>16 – 30</td>
<td>.84</td>
</tr>
<tr>
<td><strong>Auditory-FS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean Switch RT</td>
<td>3372.29</td>
<td>908.18</td>
<td>1560.89 – 5355.18</td>
<td>.97</td>
</tr>
<tr>
<td>Mean Non-switch RT</td>
<td>2614.73</td>
<td>688.36</td>
<td>1298.22 – 4756.65</td>
<td>.98</td>
</tr>
<tr>
<td><strong>Visual-FS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean Switch RT</td>
<td>3229.51</td>
<td>852.24</td>
<td>1473.02 – 5262.23</td>
<td>.98</td>
</tr>
<tr>
<td>Mean Non-switch RT</td>
<td>2482.13</td>
<td>654.55</td>
<td>1402.59 – 4229.09</td>
<td>.98</td>
</tr>
<tr>
<td><strong>Complex Memory Span</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Listening Span (Recall accuracy)</td>
<td>25.95 (65%)</td>
<td>6.70</td>
<td>11 – 40</td>
<td>.85</td>
</tr>
<tr>
<td>Counting Span (Recall accuracy)</td>
<td>23.07 (64%)</td>
<td>4.50</td>
<td>11 – 32</td>
<td>.87</td>
</tr>
</tbody>
</table>

*Note. A-Auditory; V-Visual; FS-Focus Switching; RT-Reaction time; *Cronbach’s alpha coefficient of reliability.*
Primary Adjusted Analyses

General Linear Modeling procedure was used for model estimation where complex memory span was entered as the dependent variable. The predictor variables representing sustained attentional focus, attentional focus switching accuracy, mean switch reaction time (indexing attentional focus switching speed), and the covariates age and speech rate were all entered in the model. Univariate analysis of variance revealed that jointly all the predictors contributed to significant variance in complex memory span performance. It was observed that speech rate was not a useful covariate as it was already associated with age. That is, even without speech rate in the model the relationship of the predictors to complex memory span, in the presence of age, remained unchanged. Speech rate was thus disregarded from any further analyses and discussion. The final analysis (as shown in Table 4) thus revealed that all the covariates in the model jointly explained 58% of the variance in complex memory span performance of children in the age range of 7 to 11 years, $F(4, 55) = 19.14, p < .001, R^2 = .58$.

Analysis of individual parameter estimates revealed that in the presence of age, sustained attentional focus and mean switch reaction time (i.e., attentional focus switching speed), it was only accuracy of focus switching that contributed significantly to unique variance in complex memory span performance, $\beta = .415, F(1, 55) = 11.60, p = .001$. That is, for every one unit increase in the accuracy of attentional focus switching, the predicted increase in children’s complex memory span performance was .415 (see Table 4).
Table 4

*Summary General Linear Model table of Primary Adjusted Analyses Predicting Complex Memory Span Performance Using the Predictors Sustained Attentional Focus, Attentional Focus Switching Speed, and Attentional Focus Switching Accuracy, in the Presence of Age*

<table>
<thead>
<tr>
<th>Variables in the Model</th>
<th>β</th>
<th>95% confidence interval</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lower bound</td>
<td>Upper bound</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age</td>
<td>.018</td>
<td>-.008</td>
<td>.045</td>
<td>2.00</td>
</tr>
<tr>
<td>Sustained attention</td>
<td>.098</td>
<td>-.127</td>
<td>.323</td>
<td>.76</td>
</tr>
<tr>
<td>Attentional focus</td>
<td>-.175</td>
<td>-.467</td>
<td>.117</td>
<td>1.43</td>
</tr>
<tr>
<td>Switching speed</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Attentional focus</td>
<td>.415</td>
<td>.171</td>
<td>.659</td>
<td>11.60</td>
</tr>
<tr>
<td>Switching accuracy</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Note.* \(F(4, 55) = 19.14, R^2 = .58, p < .001.\)

Secondly, change statistics were observed to determine how much additional variance in complex memory span, attentional focus switching accuracy contributed to, over and above that contributed by sustained attentional focus and attentional focus switching speed (mean switch reaction time), in the presence of age. Attentional focus switching accuracy uniquely contributed to 9% increase in variance in complex memory span when it was added to a model already containing the other predictors \(ΔF = 11.60, p = .001\).
Secondary Analyses

Correlation analyses revealed that all the experimental tasks were age sensitive (Figures 3, 4, and 5). Children’s performance on both the attention constructs (sustained attentional focus and attentional focus switching accuracy and speed) and the dependent variable (complex memory span) improved with age ($p < .001$). Partial correlations (controlling for age) between all experimental measures were also significant (see Table 5).

*Figure 3.* Developmental trend for sustained attentional focus.
Figure 4. Developmental trends for attentional focus switching accuracy and speed.
Figure 5. Developmental trend for complex memory span performance.

Table 5

Bivariate and Partial Correlations Between Composite z Scores of all Experimental Constructs and Age (N = 61)

<table>
<thead>
<tr>
<th>Variables</th>
<th>1.</th>
<th>2.</th>
<th>3.</th>
<th>4.</th>
<th>5.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Age</td>
<td>1</td>
<td>.428**</td>
<td>.483**</td>
<td>-.661**</td>
<td>.551**</td>
</tr>
<tr>
<td>2. Sustained Attention</td>
<td>1</td>
<td>1.480**</td>
<td></td>
<td>-.620**</td>
<td>.507**</td>
</tr>
<tr>
<td>3. Attentional FS accuracy</td>
<td>.349*</td>
<td>1</td>
<td>-.735**</td>
<td>.708**</td>
<td></td>
</tr>
<tr>
<td>4. Attentional FS speed</td>
<td>-.505**</td>
<td>-.632**</td>
<td>1</td>
<td>-.686**</td>
<td></td>
</tr>
<tr>
<td>5. Complex memory span</td>
<td>.354*</td>
<td>.605**</td>
<td>-.517**</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

Note. **Correlation is significant at $\alpha = .001$ (2 tailed); *Correlation is significant at $\alpha = .01$ (2 tailed). Values below the diagonal represent partial correlations after controlling for age. FS – Focus Switching.
On each of the two attentional focus switching tasks (auditory and visual) accuracy of counting on low frequency switch trials was compared with accuracy on high frequency trials. There was a significant difference between accuracy on low vs. high frequency switch trials with poorer accuracy on high frequency switch trials for both auditory ($M_{LF} = 12.67, SD = 1.77; M_{HF} = 10.96, SD = 2.76$) and visual ($M_{LF} = 13, SD = 1.59; M_{HF} = 11.85, SD = 2.32$) tasks, $t(59) = 7.75, p < .001$ and $t(60) = 5.10, p < .001$ for the auditory and visual tasks respectively (see Figure 6).

![Figure 6](image.png)

*Figure 6.* Count accuracy on trials with low and high frequency switches on the auditory and visual attentional focus switching tasks.
Mean switch reaction time was significantly longer than the mean non-switch reaction time for both auditory and visual attentional focus switching tasks (see Figure 7).

For the auditory task \( t(59) = 14.20, p < .001 \) (\( \text{Mean}_{\text{switchRT}} = 3372.29, SD = 908.18 \); \( \text{Mean}_{\text{nonswitchRT}} = 2614.73, SD = 688.36 \)) and for the visual task \( t(60) = 13.90, p < .001 \) (\( \text{Mean}_{\text{switchRT}} = 3229.51, SD = 852.24 \); \( \text{Mean}_{\text{nonswitchRT}} = 2482.13, SD = 654.55 \)).

![Figure 7. Mean reaction time on switch vs. non-switch presentations on the auditory and visual attentional focus switching tasks.](image)

As for the accuracy on the two stimuli in each task, there was no significant difference in count accuracy for high tones vs. low tones and between big squares vs. small squares \( (p > .05) \). That is, one stimulus (e.g., big square) did not show a significant advantage over the other stimulus (i.e., small square) and vice-versa in terms of accuracy.
CHAPTER 5: DISCUSSION

The present study examined two attention control mechanisms (sustained attentional focus and attentional focus switching) in 7- to 11-year-old typically developing children. The specific aim of the study was to investigate the contribution of these two attention control mechanisms to children’s complex memory span performance, adjusting for age. Complex memory span has been conventionally used as an index of working memory in both children and adults (Daneman & Carpenter, 1980; Turner & Engle, 1989). Children were administered seven experimental tasks. Two tasks were used for each predictor construct (sustained attentional focus and attentional focus switching) and the dependent variable (complex memory span).

Relation of Attention Control to Complex Memory Span

That working memory, conventionally indexed by complex memory span performance, improves with age, has been clearly demonstrated in the developmental memory literature (Case, 1985; Case et al., 1982; Cowan et al., 1999; Gathercole, 1999; Swanson, 1996, 1999; Towse et al., 1998). Developmental improvements in complex memory span have been associated with improvements in higher-order cognitive functioning. For the past three decades, the memory literature has investigated (a) what mechanisms lead to improvements in complex memory span and (b) what aspects of working memory make it such a strong predictor of high-order cognition.

As mentioned in the review, several aspects such as short-term memory storage capacity, processing efficiency, retention duration, and attention have been emphasized as critical determinants of complex memory span. While attention control has been
discussed in developmental working memory models, in the present study we examined
two control functions that have not yet been explicitly measured in their relation to
developmental working memory. Sustained attentional focus was indexed by the accurate
detection of target stimuli in a series of presented stimuli. Attentional focus switching
was represented by two variables: accuracy of focus switching and the speed of focus
switching between two distinct stimuli that were presented in varying orders to be
counted. On the focus switching task, in a sequence of presentations (i.e., each trial),
when a stimulus was the same as the previous one presented, the presentation constituted
a non-switch presentation. When the stimulus presented was different from the previous
one the presentation was called a switch presentation. The two attention control functions
were evaluated in both auditory and visual domains to increase the reliability of each
construct.

*Sustained Attentional Focus and Complex Memory Span*

In the presence of age, attentional focus switching accuracy, and focus switching
speed, sustained attentional focus failed to contribute any unique variance to complex
memory span. That is, even though sustained attentional focus was linearly related to
complex memory span, this relation had little impact in the presence of the other
predictors in the model (i.e., attentional focus switching accuracy and speed). One might
argue that sustained attentional focus is contrastive to attentional focus switching.
Sustaining attentional focus relates to maintaining attention for a prolonged duration on
any particular aspect of a task whereas attentional focus switching reflects the ability to
immediately and rapidly switch or alternate attentional focus between two aspects of a
given task. While these two constructs are clearly separable (Mirsky, Anthony, Duncan, Ahearn, & Kellam, 1991), it is helpful to consider how each might relate to complex memory span performance while at the same time appreciating how they could differ in their relative contribution to span.

As per our hypothesis, sustained focus of attention was hypothesized to be required for maintaining adequate vigilance on each processing episode and then each retrieval episode across multiple trials of the complex memory span tasks. In an absolute sense, children needed to maintain their focus of attention on an entire processing episode (e.g., comprehend the meaning of five sentences or count the number of dots on five successive computer screens) before turning their attentional focus to the retrieval component of the task in which they attempted to recall as many items as they could from short-term memory. Considering its relative importance, it appears that sustained attentional focus is less critical to complex memory span, as indexed by recall, than attentional focus switching. This could be because item recall predominantly requires an attentional refreshing mechanism to reactivate items in short-term memory. Attentional refreshing seems to be more functionally equivalent to attentional focus switching (Barrouillet et al., 2009) than sustained focus of attention. On this view, rapidly switching attentional focus between processing individual items within a given processing episode and refreshing its corresponding items in storage, may have assumed greater importance to complex span performance, than being able to sustain attentional focus over the duration of a given processing episode.
Accordingly, to further explore the weak relation of sustained attentional focus to complex memory span (relative to attentional focus switching), partial correlations between sustained attentional focus and the two measures of complex memory span (i.e., counting span and listening span) were examined. Recall that complex memory span was indexed by the composite score obtained from counting and listening span tasks, indexed by item recall. Controlling for age, sustained attentional focus correlated significantly with counting span ($r = .462$, $p < .001$) but not with listening span ($r = .111$, $p > .05$). It might be speculated that sustained focus of attention was deployed in the counting span task because it reflected the interaction of task demands and automatic cognitive processing. In this task, children were presented in rapid succession a series of dots on the computer screen, with minimal delay occurring between each display. Minimal delay likely occurred because the task required a simple counting skill, one that for 7- to 11-year-olds was highly automatic. Thus, the children essentially engaged in a continuous automatic behavior of counting which probably involved measurable amounts of sustained focus of attention across multiple processing episodes. In the listening span task, the children heard sets of sentences and were asked to judge the truth value of each. It might be argued that processing the semantic and pragmatic truth value of a sentence required more than automatic processing. On the listening span task children were required to interpret the meaning of each sentence and compare that meaning against their semantic-pragmatic knowledge. Such interpretive and comparative processing of each sentence required time, which probably prevented each sentence from being presented one after another in a fast and continuous fashion. Thus, the delay between
each sentence was necessarily longer than the delay between each screen of dots. Thus, the linguistic nature of the listening span task requiring more deliberative processing may have prevented the children from establishing a pattern of more sustained and continuous focus of attention use during each processing episode.

The discrepant relation of each of the complex memory span tasks (i.e., listening span and counting span) to sustained attentional focus explained above can also be referred to as “surplus construct irrelevancy.” Surplus construct irrelevancy relates to construct validity. It refers to task operations or dimensions that are not relevant to the target construct (Cook & Campbell, 1979). While the listening and counting span tasks were both measures of complex memory span and topographically similar (i.e., both required storage and processing), there were fundamental differences between the tasks with respect to their processing components as explained above. As a consequence of this difference, sustained attentional focus could have been more critical to counting span and not to listening span.

In support of the above view that the nature of the processing episode may influence the attentional control processes involved in complex memory span task performance, Towse and Cowan (2005) have argued that complex memory span tasks are multifaceted. That is, all complex memory span tasks cannot be regarded as comparable, and it would be an oversimplification to do so. They suggest that specific attention control functions could be involved in different ways across complex memory span tasks. For example, reading span involves more inhibitory mechanisms, while operation span tasks with word recall likely invoke greater controlled attention since the processing and
storage elements are rather distinct. Their discussion also leads to the point then that the relation of complex memory span to higher order cognition is also complex.

While every effort was made to control for task specific irrelevance on both the complex memory span tasks, a fundamental difference between the complex memory span tasks (listening span and counting span) emerged in the present study. The listening span task entailed remembering a digit appearing at the end of each sentence. Sentences were simple constructions. One critical factor that could have led to qualitative differences between the listening and counting span tasks may relate to differences in the timing aspects of the processing activity. Children continuously performed processing on the counting span task. However, in listening span, processing occurred in a more discontinuous fashion. The counting span task appeared to be more dynamic than the listening span task in requiring “continuous processing.”

In summary, the discussion of the nature of the processing activity used in complex memory span tasks informs the issue of whether to use multiple tasks to assess working memory. It reinforces the need to use latent variables as the solution to obtain the best measure of complex memory span and to avoid construct related irrelevance from influencing the relations under study. An alternative could also be more careful selection of complex memory span tasks keeping in mind domain-specific influences as well as comparable task structures given that complex memory span tasks are multifaceted.
Attentional Focus Switching and Complex Memory Span

Attentional Focus Switching Accuracy

Results were strongly in favor of attentional focus switching accuracy being a critical determinant of complex memory span. In the presence of the other predictors (sustained attentional focus, focus switching speed) and, adjusting for age, accuracy of focus switching contributed to significant unique variance in complex memory span. While attentional switching speed was also related to complex memory span, its contribution turned out to be insignificant in the presence of attentional focus switching accuracy. Such a finding is timely because it resonates well with (a) more recent conceptions of working memory mechanisms (Barrouillet et al., 2009; Cowan, 1988; McElree, 2001; Unsworth & Engle, 2007) as well as with (b) the adult literature that has recently suggested that attentional focus switching accuracy plays a role in complex memory span performance (Unsworth & Engle, 2008).

Various models of working memory have emphasized that retrieval of contents in working memory involves switching attention between items that are already in the focus of attention to the ones that are currently activated but need attention to be retrieved (Barrouillet et al., 2009; Cowan, 1988; McElree, 2001; Oberauer, 2002). Accordingly, in the present study, children who were more accurate in switching their attention to the appropriate element also demonstrated better complex memory span performance.

Accuracy of counting was further evaluated as a function of the frequency of switches within a trial. Accuracy of updating counts suffered with increase in the frequency of switches within a trial. That is, mean accuracy was significantly lower on high frequency
switch trials in comparison to low frequency switch trials. This can be taken to suggest that frequent instances of switching can be taxing to children’s attention system. On complex memory span tasks increasing the pace of the processing component or controlling processing time (e.g., Barrouillet et al., 2009) could inherently render this switching process more prone to errors (i.e., children may switch to the incorrect element) and at the same time allow for fewer retrievals, thus leading to a detrimental effect on complex memory span.

Finally, just like the adults (Unsworth & Engle, 2008) children demonstrated switch costs. That is, children’s mean switch reaction times were longer than mean non-switch reaction times suggesting that retrieving an item which is already in the focus of attention is easier and less attention demanding than retrieving an item that is outside the current focus of attention. Processing elements of any complex memory span task thus function to deviate attention from recall and thus introduce such a need for switching attention during processing for refreshing of recall elements that are active but outside the focus of attention.

The role of attentional focus switching not only assumes an important position in recent developmental models of working memory but also relates to aspects of the domain-general component of several working memory models. That is, while executive control/controlled attention has been emphasized in the working memory literature (Baddeley, 1996, 2003; Conway & Engle, 1996; Engle, Kane, et al., 1999; Engle, Tuholski, et al., 1999), it has not yet been clearly specified in children (Zoelch et al., 2005). One of the stated reasons for this lack of specificity is that the executive is a broad
term which could comprise several processes, with deployment depending on the nature of the cognitive task at hand (Baddeley, 1996; Towse & Houston-Price, 2001; Zoelch et al., 2005). For example, according to a few studies in children and adults, a task like random generation (Baddeley, 1996) designed to assess executive functioning is neither the only measure nor the best measure to tap the role of the executive in working memory (Towse & Houston-Price, 2001; Zoelch et al., 2005). This is because a task like random generation is said to comprise multiple cognitive processes (Towse & McLachlan, 1999). Similarly, there are numerous tasks that have been used to index various processes of the central executive but each task appears to be multiply determined (Zoelch et al., 2005). It is important thus to devise tasks that best represent specific attention control mechanisms that most closely relate to complex memory span performance.

In the present study, we adopted a theory neutral view of working memory. That is, we assessed attentional control mechanisms not assumed by any particular theoretical model of working memory. Rather our approach was based on the premise that the predictive value of working memory has been shown to largely lie in its domain-general aspect, which is attention. Attention, as a separate superordinate construct, is clearly associated with working memory. Since attention itself is multidimensional, it is not clear which aspects of attention should be relatively important to working memory. In the present study, attention control functions were evaluated because of the lack of research explicitly quantifying these in children. There is also emerging literature suggesting that children rapidly switch their focus of attention between storage and processing functions in working memory. This has been inferred from continuous span tasks where processing
time is controlled and children perform simple processing tasks interleaved with recall elements (Barrouillet et al., 2009).

Even while the complex memory span tasks used in the present study were not strictly time controlled, each processing item was presented by the experimenter immediately after the previous processing episode ended. This was especially so in the counting span task where children continuously counted dots. That is, since counting as a skill was more practiced, children’s performance on the task was very rapid and fluid. By contrast, in the listening span task, the time by which children responded to the sentence meaning was longer and more variable. Children’s performance on sentence plausibility judgments were discontinuous in terms of timing when compared with continuous counting on the counting span task. In the present study, the topography of the complex memory span tasks differed from the time-controlled continuous span tasks used by Barrouillet and colleagues who have emphasized the role of attentional focus switching in children. Inspite of this difference in task design between the present study and the studies by Barrouillet and colleagues, attentional focus switching ability in terms of accuracy still emerged as a strong predictor of complex memory span. This finding might be taken as evidence that accuracy of focus switching is a robust predictor of complex memory span. It then logically follows that controlling the duration of the processing episode or increasing the pace of the processing episode of complex memory span task would tax the attentional switching mechanism even greater.
Attentional Focus Switching Speed

Our results also indicate that while the accuracy of the attentional focus switching mechanism (i.e., retrieving the correct element from active memory) is a robust predictor of complex memory span performance the speed at which children perform this switch is not. In the presence of sustained attentional focus, attentional focus switching accuracy and controlling for age effects, mean switch reaction time did not contribute to any unique variance in complex memory span performance. This finding mirrors the findings from the adult literature where accuracy of focus switching was related to working memory and higher-order cognitive functioning but focus switching speed was not (Unsworth & Engle, 2008). These authors considered speed-accuracy trade-off as one alternative explanation for such a finding. That is, low span participants in their study could have sacrificed accuracy for speed since participants were instructed to perform as fast and accurately as possible. Correlations were examined to check for such a possibility and the authors found that individuals in their study did not trade accuracy for speed (i.e., the correlation between overall switch speed and accuracy was not significantly negative). Similarly, in our study, we discarded the possibility that children who were more accurate switchers were slower in focus switching speed. Secondary analyses showed that, controlling for age, there was a significant positive linear relationship between speed of switching on both non-switch and switch presentations and accuracy of attentional focus switching ($r = -.427$, $p < .001$ and $r = -.632$, $p < .001$, respectively). That is, children who were more accurate on attentional focus switching were also faster in terms of switching speed. A speed-accuracy trade-off was thus not
responsible for reducing the impact of attentional focus switching speed to children’s complex memory span.

Shared variance could be one of the factors that caused speed of switching to be insignificant in the presence of the other predictors. Secondary analyses pointed out that, while switching speed did contribute unique variance (11%) to complex memory span over and above that contributed jointly by age and sustained attentional focus, when attentional focus switching accuracy was added to the final model, attentional switching speed ceased to be significant. This might also logically imply that attentional focus switching speed and accuracy comprise a chain relation towards complex memory span performance, because of which when accuracy is added to the model the relation between focus switching speed and complex memory span disappears. That is, faster switching speed contributed to greater accuracy (indirectly reducing the retention interval during which decay was plausible), which was, in turn, related to complex memory span. In summary, adjusting for all other predictors focus switching accuracy remained the strongest unique predictor of complex memory span performance in 7- to 11-year-old children.

Developmental Trends of the Examined Variables

Recalling the developmental aspects of the attention control variables used in the present study is relevant, because they contribute to developmental improvements in complex memory span. The relation of the attention variables to age also supports our motivation to include children between the ages of 7 and 11 in the present study.
Additionally, the developmental trends also suggest that the experimental tasks constructed for the present study were age sensitive.

Children’s performance on the attention control tasks and complex memory span increased as a function of age. This finding was expected, because children’s attention control skills have been extensively studied, albeit more often independent from a working memory perspective. Attention control, for example, has been studied from an attention deficit disorder perspective, for developing normative data on developmental attentional abilities and for developing tests of attention (e.g., Barkley, 1996; Jones et al., 2003; Manly et al., 2001). Children’s sustained attention skills as indexed by various continuous performance tasks show a clear increase especially between age 6 and 12 years with lesser distinction between 12-year-olds, adolescents, and adults, indicating plateauing on certain mental processes. Similarly, findings by Pearson and Lane (1991) on auditory attention switching in children indicated that attentional switching ability is significantly different between 8-year-olds and 11-year-olds. Eleven-year-olds were faster and more accurate than the 8-year-olds on attentional switching. It is important to note that even though the 8-year-olds in the Pearson and Lane (1991) study did not perform as well as the older children they did have the ability to switch their attention to a second source when instructed. Other studies exploring multiple executive functions in children also clearly indicate that executive control functions improve with age (Zoelch et al., 2005).

In consonance with the developmental literature, children’s sustained attentional focus as observed in the present study improved as a function of age (Barkley 1996;
Jones et al., 2003; Manly et al., 2001). The developmental literature suggests that one type of measure (e.g., continuous performance tasks) may not be sufficient to reflect a single underlying construct (Cook & Campbell, 1979). Multiple processes (e.g., motivation, environmental factors) could also affect a single measure assumed to index a single construct (Cook & Campbell, 1979; Zoelch et al., 2005). While latent variables from different types of measures are the best representatives of a construct, such an approach was beyond the scope of the present study.

In the present study, patterns similar to those reported in the previous literature were also obtained on the attentional focus switching task. It was observed that even the youngest children (the 7-year-olds) were able to perform the attentional focus switching tasks, but were slow in overall speed of performance in comparison to the older children: partial correlation between age and mean switch reaction time controlling for speech rate was moderate $r = -.583, p < .001$. The younger children, especially the 7-year-olds, also demonstrated greater fatigue on the task compared to older children reflecting the greater demand placed by the task on their overall attentional resources. Two of the 61 children used their fingers to facilitate keeping track of the two distinct stimuli while performing the task, reflecting at least one overt strategy children might actively incorporate when challenged with attentional requirements. Literature also suggests that such overt attentional strategies are refined during early school years (Pearson & Lane, 1991). Overall, performance on the attention control tasks demonstrated a qualitative as well as quantitative improvement in performance with increase in age.
Performance on both the complex memory span tasks (listening and counting span) was also age sensitive. In consonance with the developmental memory literature (e.g., Barrouillet et al., 2009; Case et al., 1982) children’s performance improved significantly as a function of age (see Figure 5). There were no floor or ceiling effects across the age range studied.

Strengths of the Present Study

One of the strengths of the present study lies in the relatively wide age range of children studied. The attentional focus switching study predicting complex memory span in adults (Unsworth & Engle, 2008) used an extreme group design. While such designs are commonly used it is advisable to study significant relations in a wide distribution of participants (Conway et al., 2005; Unsworth & Engle, 2008). Second, the present study utilized tasks from both auditory and visual domains to minimize domain-specific task confounds from unduly affecting the results. Utilizing multiple measures for constructs under study has been repeatedly emphasized in the attention and memory literatures (Conway et al., 2005; Morris, 1996; Towse & Cowan, 2005). Third, several critical task features were incorporated from the attention and memory literature. For example, (a) recall on the listening span involved recalling a separate number instead of the last word of the sentence (Conway et al., 2005); and, (b) children were allowed to report counts on the attentional focus switching tasks in any order that was facilitative to them rather than a requirement to report counts in a fixed order (Unsworth & Engle, 2008). Future studies will extend the project keeping in view some of the limitations of the study and research directions that have been listed below.
Limitations of the Present Study

While the present study provides important and significant insights into attention control mechanisms in typically developing children’s complex memory span, it has a few inherent limitations. The first is that each of the relevant constructs under study was derived by creating composite scores from two different tasks. While the composite score reflects the average performance on a construct, one limitation of this approach is that task specific influences are not eliminated from the overall performance. Perhaps more preferable would be to use a latent variable approach in which a single outcome extracted from multiple tasks represents only the latent factor/construct common to the individual tasks. Task specific irrelevance also has to be also kept in mind and must be addressed with caution. For example, in the present study listening span and counting span though represented the same construct (complex memory span) demonstrated some fundamental differences in their underlying processes especially given their relation to sustained attention. Finally, while attentional focus switching tasks involved simple counting of numbers ranging from 1-11, individual differences in children’s counting abilities may influence count accuracy and speed. Such an influence, though not systematically observed in the present study, might need to be controlled in future studies even if the study involves only typically developing children.

Future Directions

In the present study attentional focus switching accuracy emerged as the single unique predictor of complex memory span performance in the presence of sustained attentional focus, attentional focus switching speed, and age. While attentional focus
switching accuracy seems to be a critical determinant of complex memory span, it may not be the sole attentional constraint to developmental working memory. For example, inhibition is at least one other attention control variable that has received some research focus in the adult literature (Kane et al., 2001; Hasher et al., 2008) but very little attention in children’s complex memory span performance.

Secondly, factors such as domain-specific storage abilities and processing efficiency are other known variables associated with children’s complex memory span performance that might contribute to part of the unexplained variance (Bayliss et al., 2003, 2005). Future studies must incorporate attention mechanisms along with short-term memory and processing efficiency measures in discussing the relative contribution of each of these mechanisms to children’s complex memory span. This would allow better convergence of multiple theoretical models of children’s working memory. Such an analysis might also help us understand the predictive value of working memory to higher-order cognition better, and would also help understand developmental improvements in children’s complex memory span abilities.
REFERENCES


APPENDIX A: DEVELOPMENTAL QUESTIONNAIRE

The parents first answered a developmental questionnaire. It included questions on developmental milestones and academic skills to rule out history of any form of developmental delay, sensory-motor or neurological deficits. The children included in this study needed 1.) to qualify as typically developing and 2.) to be fluent speakers of English (based on language screening)

*Examples from questionnaire:*

1. Do you have any concerns right now about your child’s speech and language abilities?
2. Has your child ever been diagnosed as having neurological problems such as seizures, cerebral palsy or having a severe head injury?
APPENDIX B: INSTRUCTIONS FOR THE AUDITORY SUSTAINED ATTENTION TASK

“Now we’re going to play a listening game. You will wear these headphones and listen to a man saying a whole bunch of numbers, one right after the other. I want you to listen very carefully for when he says the numbers ‘1, 9’ right after each other. Every time he says ‘1, 9’, I want you to quickly press this blue button. You’ll need to press it pretty hard, like this” (Examiner demonstrates).

“The trick is that the man will say the number ‘9’ a lot of times but I want you to press the button only when he says ‘1’ and ‘9’ together, right after each other. So try not to hit the button when you hear the number ‘9’ after other numbers. If you do hit the button when you shouldn’t, don’t worry about it. Just wait for the next time you hear the numbers ‘1, 9’.”

Performance (using live voice) will be first demonstrated by the examiner. This would be followed by the child’s practice trials (using live voice) “Now it’s your turn to practice. I’m going to read some numbers and you push the button every time you hear me say ‘1, 9’.”

“2,3,4,1,7,9,4,1,9,8,2,1,3,9,1,3,1,9,2,8,7,2,5,4,6,9,3,1,9,4,1” “Great, you have the idea.”

Before the test trials commence the following instruction is given: “I’ll sit here and wait until you are done. You’ll know when the game is over because the green light will come on. If you have any questions or want to talk about the game after we have started, I want you to wait until after the game is over, and we can talk then. Ready to listen for ….‘1, 9’?”
APPENDIX C: INSTRUCTIONS FOR THE VISUAL SUSTAINED ATTENTION TASK

“Now we’re going to play a game. You will look at this little screen and see whole bunch of numbers, one right after the other. I want you to watch very carefully for the numbers ‘1, 9’ coming right after each other. Every time you see ‘1, 9’, I want you to quickly press this blue button. You’ll need to press it pretty hard, like this” (Examiner demonstrates).

“The trick is that you will see the number ‘9’ a lot of times but I want you to press the button only when you see ‘1’ and ‘9’ together, right after each other. So try not to hit the button when you see the number ‘9’ after other numbers. If you do hit the button when you shouldn’t, don’t worry about it. Just wait for the next time you see the numbers ‘1, 9’.”

Performance (using live voice) will be first demonstrated by the examiner. This would be followed by the child’s practice trials (using live voice) “Now it’s your turn to practice. I’m going to read some numbers and you push the button every time you hear me say ‘1, 9’.”

“2,3,4,1,7,9,4,1,9,8,2,1,3,9,1,3,1,9,2,8,7,2,5,4,6,9,3,1,9,4,1” “Great, you have the idea.”

Before the test trials commence the following instruction is given: “I’ll sit here and wait until you are done. You’ll know when the game is over because the green light will come on. If you have any questions or want to talk about the game after we have started, I want you to wait until after the game is over, and we can talk then. Ready to watch out for ….‘1, 9’?”
APPENDIX D: INSTRUCTIONS FOR THE AUDITORY ATTENTIONAL FOCUS SWITCHING TASK

“This is a listening game where you will hear and count beeps. You will hear two kinds of beeps – a low beep and a high beep. As you hear each beep you need to keep count of them. Remember you have to keep count of both the low and high beeps even though you will hear only one at a time.

Once you have updated your count press the space bar immediately for the next beep. You will know that the trial is over when you see the screen turn green. At this time you need to tell me how many high and low beeps you heard/counted. You can tell them to me in any order high/low or low/high.

Remember you need to be as accurate and fast as possible.”

(Examiner demonstrates 2 trials at two different sequence lengths)

This is followed by 3 practice trials till the child has understood task expectations well which will be indicated by the child’s accurate performance on at least 2 of 3 practice trials.
APPENDIX E: INSTRUCTIONS FOR THE VISUAL ATTENTIONAL FOCUS SWITCHING TASK

“This is a counting game where you will see squares on this screen one by one. You will see two kinds of squares – a small red square and a big red square. As you see each square you need to keep count of them. Remember you have to keep count of both the small square and the big square even though you will see only one at a time.

Once you have updated your count press the space bar immediately for the next square. You will know that the trial is over when you see the screen turn green. At this time you need to tell me how many small and big squares you saw/counted. You can tell them to me in any order small/big or big/small.

Remember you need to be as accurate and fast as possible.”

(Examiner demonstrates 2 trials at two different sequence lengths)

This is followed by 3 practice trials till the child has understood task expectations well which will be indicated by the child’s accurate performance on at least 2 of 3 practice trials.
APPENDIX F: ITEMS FOR SPEECH PRODUCTION RATE MEASUREMENT

“Say the following words as fast as you can”. (Children are shown each list for familiarization and are also demonstrated how to count automatically and fast. Children do not read the items, they just say them out for the final speech rate recording).

List 1
0 high 1 high 2 high…………………10 high 0 low 1 low 2 low……………….10 low

List 2
0 big 1 big 2 big …………….10 big 0 small 1 small 2 small……………….10 small