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Working Memory Deficits in Children: Contributions of Executive Control Processes and Symptoms of ADHD

Stacie Leffard

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WORKING MEMORY DEFICITS IN CHILDREN: CONTRIBUTIONS OF
EXECUTIVE CONTROL PROCESSES AND SYMPTOMS OF ADHD

by

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Submitted in partial fulfillment of

the requirements for the degree

Doctor of Philosophy

School Psychology Doctoral Program

Department of Counseling, Psychology, and Special Education

School of Education

Duquesne University

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Stacie A. Leffard

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Dissertation

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**WORKING MEMORY DEFICITS IN CHILDREN: CONTRIBUTIONS OF
EXECUTIVE CONTROL PROCESSES AND SYMPTOMS OF ADHD**

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ABSTRACT

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August 2008

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The most empirically supported model of working memory contains four components: (a) the phonological loop, (b) the visuospatial sketchpad, (c) the episodic buffer, and (d) the central executive (Baddeley & Hitch, 1974; Baddeley, 2003). The central executive has been fractionated into four subprocesses: (a) sustained attention, (b) selective attention/inhibition (c) shifting attention, and (d) control of retrieval from long-term memory (Baddeley, 2003; Mirsky et al., 1991; Zoelch et al., 2005). Children with ADHD are known to have working memory deficits, though the role of each component of the working memory system in these deficits is not known. The purpose of the current study is to examine the relationships between (a) symptoms of ADHD and working memory performance, (b) central executive processes and working memory performance, and (c) the unique contributions of each fractionated central executive process to the relationship between symptoms of ADHD and working memory performance. Eighty-five children

ages 8 to 16 from an outpatient clinical database were included in the study sample. Sustained attention was found to contribute unique variance to working memory performance after controlling for short-term memory. Selective attention/inhibition, shifting attention, and control of retrieval from long-term memory did not contribute unique variance to working memory, though limited power may have affected results. ADHD symptoms did not correlate with working memory, but they did correlate with short-term memory. Sustained attention was then examined as a mediator between ADHD hyperactivity symptoms and short-term memory. Though not a significant mediator, results of mediation procedures appear to indicate partial mediation. Results indicate that sustained attention may be a fractionated process of the central executive. They also suggest that ADHD symptoms may interfere with working memory at the short-term memory and executive levels. Further investigation is suggested to explain relationships between executive processes and working memory performance and between symptoms of ADHD and all components of the working memory system.

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CHAPTER I

INTRODUCTION

Attention-deficit/hyperactivity disorder (ADHD) is a neurocognitive disorder characterized by deficits in executive functions resulting in behavioral symptoms of hyperactivity and inattention (Barkley, 1997). One consistent cognitive deficit associated with ADHD is that of working memory (Barkley, 1997; Brown, 2006; Nigg & Casey, 2005).

Working memory is a set of cognitive processes that interact to retain and manipulate information needed for completion of daily activities (Baddeley, 2003). Examples of processes included in the working memory system include rehearsal, retrieval, manipulation, and controlled attention. The working memory system is primarily localized in the dorsolateral prefrontal cortex with involvement of the visual cortex in the occipital lobe and the language cortex in the left temporal lobe (Baddeley, 2003). Though normal functioning of the working memory system is generally understood (Baddeley, 2003; Engle, 2002; Oberauer et al., 2003), the nature of working memory deficits in relation to specific psychiatric disorders, such as ADHD, is less well understood (Barkley, 1997; Shallice et al., 2002). As working memory is identified as a key executive deficit in ADHD (Barkley, 1997; Brown, 2006; Nigg & Casey, 2006), comprehensive understanding of working memory in this population, and the relationships between symptoms of this disorder and working memory dysfunction, is essential for successful intervention.

In order to make hypotheses as to which processes in the working memory system contribute to working memory deficits in children with symptoms of ADHD, proposed

models of working memory will be examined. The relationship of these theories to working memory performance in individuals with ADHD will then be discussed. This information will be used to hypothesize which components of the working memory system contribute to the relationship between working memory deficits and symptoms of ADHD.

Practical Application of Working Memory Research

The working memory system facilitates learning through the processes of storage, rehearsal, retrieval of information from long-term memory, and control of attention (Baddeley, 2003; O'Reilly & Frank, 2006). If a child has a dysfunctional working memory system then they are likely to have difficulty with school performance (St. Clair-Thompson & Gathercole, 2006). Working memory has been empirically linked to performance in multiple areas of achievement including math and English (Bull & Scerif, 2001; St. Clair-Thompson & Gathercole, 2006).

It has been shown that working memory performance can be improved by intervention (Klingberg et al., 2005; Klingberg, Forssberg, & Westerberg, 2002). These improvements are also reflected in imaging studies in which working memory interventions resulted in increased prefrontal and parietal lobe activity (Olesen, Westerberg, & Klingberg, 2004). When an individual is identified to have a memory deficit, current interventions suggested in the rehabilitation literature include practice and rehearsal, mnemonic strategies, external aides, and cuing (Glisky & Glisky, 2002). Interventions such as increasing rehearsal are effective if the rehearsal process in the working memory system is the source of the deficit. If, however, the deficit is in manipulation of information or control of attention, these interventions will not be

effective. In children with symptoms of ADHD, it is necessary to understand the specific processes involved in their working memory dysfunction so that appropriate, process-specific interventions can be developed and implemented. By targeting the processing deficit in the working memory system, interventions can be designed to improve or compensate for that process, thereby improving working memory functioning and performance in achievement areas requiring the use of working memory.

Current Conceptualization of Working Memory

The most empirically supported model of working memory is Baddeley's model (2003). Initially conceptualized as a three component model (Baddeley & Hitch, 1974), the current revision is a four component model. Those components are the phonological loop, visuospatial sketchpad, episodic buffer, and central executive. The phonological loop is responsible for rehearsal and storage of verbal information and is divided into two subprocesses. The phonological store is the storage mechanism. The articulatory control process is the rehearsal component of the phonological loop that refreshes information through subvocal rehearsal. The visuospatial sketchpad is responsible for storage and maintenance of visual and spatial information. This component also has two subprocesses: the inner scribe and the visual cache. The inner scribe is an active component responsible for maintenance of spatial and movement information; whereas, the visual cache is a passive storage component for visual images. The central executive is currently conceptualized as an attentional control system. It has been divided into four subprocesses: inhibition or focusing attention, dividing attention, shifting between multiple stimuli, and control of retrieval from long-term memory (Baddeley, 2002a). This retrieval of information from long-term memory, controlled by the central executive, is

carried out by the episodic buffer, the latest addition to the Baddeley model. It serves as a link between other components of the working memory system and long-term memory (Baddeley, 2003).

Though initially based on results of research on adults, Baddeley's model has also been found to explain working memory in children. Alloway and colleagues (2004) used structural equation modeling to find that Baddeley's model was the best model fit for working memory measures and related processes in a sample of 4 to 6 year-olds. The multicomponent model was a better fit than a unitary or two component model. These results indicate that Baddeley's model can be assessed in children as young as early elementary age. Zoelch and colleagues (2005) also found support for fractionated components of the central executive in children. Based on differences in effect size, they found four subprocesses: (a) selective attention and inhibition processes, (b) the coordination of simultaneous tasks and task switching, (c) the control of encoding and retrieval strategies, and (d) retrieval of information from long-term memory.

Though it is clear that the central executive is comprised of multiple processes, there are inconsistencies in the experimental working memory literature as to the specific fractionated processes of the central executive (Baddeley, 2002a; Zoelch, Seitz, & Schumann-Hengsteler, 2005). Because the central executive is referred to as an attentional control system (Baddeley, 2003), literature regarding the components of the attention system can be used to suggest essential components of attentional control to be included in the central executive construct. These components found in numerous factor-analytic studies are selective attention/inhibition, sustained attention, and coordination/shifting attention (Manly et al., 2001; Mirsky et al., 1991; Posner & Raichle,

1994; Robertson et al., 1996; Swanson et al., 1998; Tsal, Shalev, & Mevorach, 2005). These processes are similar to those found in the working memory literature; however, they have greater empirical support and will therefore be included in the current model. In addition, as control of retrieval from long-term memory is a consistent component of the central executive identified in the working memory literature (Baddeley, 2002a, 2003; Zoelch et al., 2005) it will also be included in the model. Therefore, the model of the central executive utilized in the current study will include four component processes: (a) selective attention/inhibition, (b) sustained attention, (c) shifting attention, and (d) control of retrieval from long-term memory. Selective attention/inhibition is defined as the capacity to focus on important stimuli while suppressing irrelevant stimuli (Lezak et al., 2004; Mirsky et al., 1991). Sustained attention is defined as the capacity to maintain attention over time (Lezak et al., 2004; Mirsky et al., 1991). Shifting attention is defined as the ability to change focus in a flexible manner (Lezak et al., 2004; Mirsky et al., 1991).

Working Memory and ADHD

In addition to explaining working memory performance in normal children, there is also evidence that Baddeley's model fits the patterns of working memory performance in children with ADHD. Children with ADHD generally have equivalent performance to normal controls on measures that tap the phonological loop (Karatekin, 2004; McInnes et al., 2003) and visuospatial sketchpad (Goldberg et al., 2005; Karatekin, 2004). On measures of the central executive, children with ADHD have deficient performance as compared to control children (Cornoldi et al., 2001; Fuggetta, 2006; Goldberg et al., 2005; Karatekin, 2004; Martinussen et al., 2005; Valera et al., 2005; Willcutt et al.,

2005). Results of these studies indicate that the deficits in working memory performance are a result of deficient central executive performance. Karatekin (2004) provides the strongest evidence that the differences in working memory performance are located in the central executive. On a phonological loop measure, remembering letters, and a visuospatial sketchpad measure, remembering locations of letters, children with ADHD and controls ages 8 to 15 had equivalent performance. When required to simultaneously perform a forward digit span task and a reaction task measure, the coordination of which requires central executive functioning, children with ADHD had significantly longer reaction times than control children indicating comparative deficits in this area.

Though there is evidence that working memory dysfunction occurs at the central executive level rather than the slave system level, there is not available evidence as to which of the fractionated central executive processes contribute to working memory dysfunction. There is strong evidence that children with ADHD have deficits on tasks that measure sustained attention (Heaton et al., 2001; Kerns, McInerney, & Wilde, 2001; Manly et al., 2001; Muir-Broddus et al., 2002; Shallice et al., 2002; Tsal, Shalev, & Mevorach, 2005). Children with ADHD had lower levels of performance on sustained attention measures in all available studies.

There is also strong evidence for a deficit in selective attention/inhibition (Berlin, Bohlin, & Rydell, 2003; Berlin et al., 2004; Chhabildas, Pennington, & Willcutt, 2001; Cornaldi et al., 2001; Loge, Stanton, & Beatty, 1990; Manly et al., 2001; Muir-Broddus et al., 2001; Shallice et al., 2002; Stevens et al., 2002; Willcutt et al., 2005). There are a few studies that did not find significant group differences between children with ADHD and controls (Barkley et al., 2001; Goldberg et al., 2005; Kerns, McInerney, & Wilde,

2001); however, the theoretical and empirical consensus is that children with ADHD do have selective attention/inhibition deficits relative to control children.

Performance of children with ADHD on the construct shifting attention is inconsistent. Equivalent numbers of studies indicate that children with ADHD do (Fuggetta, 2006; Heaton et al., 2001; Manly et al., 2001; Shallice et al., 2002; Willcutt et al., 2005) and do not (Goldberg et al., 2005; Loge, Stanton, & Beaty, 1990; Scheres et al., 2004) differ from control children on these measures. Children with ADHD have also been shown to have more difficulty controlling retrieval of information from long-term memory as compared to controls (Loge, Stanton, & Beatty, 1990; Scheres et al., 2004); however, a majority of the research indicates that children with ADHD do not differ from controls in this area (Barkley et al., 2001; Shallice et al., 2002; Tucha et al., 2005). It should also be noted that there are noticeably fewer studies examining group differences on this executive function. The totality of these results indicates that there is strong evidence that children with ADHD have deficient performance in two fractionated areas of the central executive: selective attention/inhibition and sustained attention. The research is inconclusive in terms of deficits in the areas of shifting attention and control of retrieval of information from long-term memory.

Critical Analysis of Current Literature

In the ADHD literature, there are several areas for improvement regarding sample characteristics. First, there is inconsistency in the literature as to what diagnostic criteria should be used to classify participants as ADHD. Some studies utilized rating scales as the only criteria whereas others rely on the DSM-IV criteria. In order to account for heterogeneity of symptoms and symptom severity within the ADHD population,

symptoms of ADHD will be included as a continuous variable in a clinical sample rather than a dichotomous variable utilizing DSM-IV-TR criteria to establish whether a child does or does not have the disorder and assuming homogeneity of the ADHD sample.

Another diagnostic issue often neglected in the ADHD literature is that of subtypes of the diagnosis. Many studies discuss only one broad category of ADHD rather than evaluating for subtype (i.e. Inattentive, Hyperactive-Impulsive, and Combined) differences in their sample. The literature is mixed regarding whether or not executive functions performance differs among ADHD subtypes (Gioia et al., 2002; Heaton et al., 2001; Tsal, Shalev, & Mevorach, 2005; Willcutt et al., 2005). In addition, the relationship between inattentive symptoms of ADHD and executive functions is stronger than the relationship between hyperactivity symptoms and executive functions (Chhabildas, Pennington, & Willcutt, 2001). Based on this information, it is necessary to examine the three domains of ADHD symptoms in the DSM-IV-TR (inattention, hyperactivity, and impulsivity) as distinct variables, each having potential for a different relationship with central executive processes and working memory.

Critical review of studies examining executive functions, including working memory, in the ADHD population reveals several areas for improvement of research designs. One research design issue is that researchers often utilize experimental measures. These measures are designed by each individual researcher. Raw scores are used in analyses. There is no basis for normed comparisons and reliability and validity of the measure is not typically established. This becomes problematic when assessing children. Because the researchers do not utilize normed measures they are often forced to add age as a covariate in the analysis. The current study strives to use normed instruments

with empirically established reliability and validity. By using standard scores on all measures, each score will be reflective of a child's performance relative to same age peers rather than only relative to the study sample. This eliminates the need for an additional age covariate.

As previously illustrated, many studies have examined group differences between children with ADHD and normal controls; however, these studies consistently fail to address the interrelationships among executive functions. The typical research design and analysis in this research area is a multivariate analysis of variance, with diagnostic group as the independent variable and various executive processes as dependent variables. Follow-up univariate analyses of variance are then completed to evaluate group differences for each executive function. As univariate analyses of variance do not address the inter-correlations among dependent variables, these studies fail to address the theoretical and empirical research that clearly indicate that executive functions do not operate in isolation from each other but in systems, such as those suggested by Barkley (1997) and Nigg and Casey (2005). Rather than examining executive functions and working memory in isolation, the current study strives to examine the interrelationships between executive processes and working memory based on theoretically and empirically supported relationships and the relationships between these interrelated processes and symptoms of ADHD.

Problem Statement

Though it is understood that the central executive is the source of working memory dysfunction in children with ADHD and that some studies have shown that children with ADHD exhibit deficient performance in each of the four fractionated

central executive processes, it is currently unknown which fractionated central executive process or combination of processes accounts for the relationship between symptoms of ADHD and working memory performance. The purpose of the current study is to determine which fractionated central executive process or processes mediate the relationship between symptoms of ADHD and working memory performance.

Research questions:

1. Which processes of the central executive (sustained attention, selective attention/inhibition, shifting attention, and/or control of retrieval from long-term memory) explain variance in working memory performance?

Hypothesis 1: Each of the four processes of the central executive will explain unique variance in working memory performance.

2. Which symptom domain of ADHD (hyperactive, impulsive, or inattentive) has the strongest relationship with working memory performance?

Hypothesis 2: Inattentive symptoms of ADHD will have a stronger relationship with working memory performance as compared to hyperactive or impulsive symptoms.

Hypothesis 3: Hyperactive symptoms will not account for additional working memory variance after accounting for variance in inattentive symptoms.

Hypothesis 4: Impulsive symptoms will not account for additional working memory variance after accounting for variance in inattentive symptoms.

3. Which process(es) of the central executive (sustained attention, selective attention/inhibition, shifting attention, or control of retrieval from long-term memory as determined by research question 1) mediate the relationship between symptoms of

ADHD (inattentive, hyperactive, or impulsive as determined by research question 2) and working memory performance?

Hypothesis 5: Sustained attention will be a significant mediator of the relationship between ADHD symptoms and working memory.

Hypothesis 6: Selective attention/inhibition will be a significant mediator of the relationship between ADHD symptoms and working memory.

Hypothesis 7: Shifting attention will account for some variance in the relationship between symptoms and working memory, but not enough to be a significant mediator.

Hypothesis 8: Control of retrieval from long-term memory will not mediate the relationship between ADHD symptoms and working memory

CHAPTER II

LITERATURE REVIEW

For the purpose of understanding working memory deficits in children with ADHD, the following literature review will examine proposed models of working memory and derive conclusions as to the most empirically and theoretically sound model to be utilized in the current study. Models of executive functions in ADHD and the relationship of these models to working memory performance in individuals with ADHD will then be discussed. This information will be used to hypothesize relationships between ADHD symptoms, component processes of the working memory system, and overall working memory performance.

WORKING MEMORY

Working memory is most commonly used to describe processes involved in holding and manipulating information in consciousness for a short period of time. Prior to development of the term working memory, memory across short periods of time was conceptualized as a single short-term storage process (Atkinson & Schiffrin, 1968). New ideas emerged through computational models using computers to simulate human memory functions (Newell & Simon, 1972) and animal behavior research (Olton, 1979). In 1974, the current theoretically supported multicomponent model of the short-term storage systems was developed and gained empirical support (Baddeley & Hitch, 1974; Baddeley, 1986). At this time the name short-term storage was changed to working memory to reflect the processing functions included in the new models in addition to the storage functions attributed to the old short-term store.

Working Memory Models

Current models of working memory functioning include multicomponent models that include multiple processes that interact to complete working memory tasks and unitary models proposing one function. Multicomponent models of working memory include those of Baddeley and Hitch (1974), Cowan (1999), and Oberauer and colleagues (2003). These multicomponent models describe working memory functioning in terms of separate but related processes or components that together result in completion of working memory tasks. In contrast to the multicomponent models, Daneman and Carpenter (1980) and Engle and colleagues (Engle 2002; Kane et al., 2004) advocate for a unitary model of working memory. Unitary models illustrate working memory in terms of one component that may take multiple roles such as both storage and processing.

Multicomponent Models

Baddeley's Model

The most empirically researched model of working memory today was initially developed by Baddeley and Hitch (1974) as a three component system. The components of the system were derived from dual task experiments in which performing two verbal tasks or two visuospatial tasks at the same time resulted in interference; however, performing one verbal and one visuospatial task at the same time did not result in interference. It was concluded from these results that there are separate verbal and visuospatial components of the working memory model. The central executive was established as a homuncular component that directed cognitive resources to these verbal and visuospatial slave systems. As research on this model has evolved, so has the model. It now includes four components (Baddeley, 2003). The components are: (a) the

phonological loop, another slave system that processes verbal and auditory information, (b) the visuospatial sketchpad, another slave system that processes visual and spatial information, (c) the central executive, a control system that directs resources to two slave systems, and (d) the episodic buffer, responsible for information transfer between the working memory slave systems and long-term memory.

Phonological loop. The phonological loop (PL), the first of Baddeley's two slave systems under the control of the central executive, is responsible for processing language-based information. It is the most empirically-supported of the working memory components. This is due to the ease of measuring and manipulating performance on phonological tasks (Baddeley, 2003). Because phonological information rather than the meaning of information caused interference in recall, it was determined that this verbal memory component is based in phonological information rather than semantic (Baddeley, 1966). Burgess and Hitch (1999) fractionated the PL into two components: the *phonological store* for storing information and the *articulatory control process* for rehearsal and recoding. The capacity of the PL is limited to a few seconds; however, the information can be refreshed so that it stays in the loop and stays accessible. Information that enters the PL is rehearsed through subvocal rehearsal (Baddeley, 2003). When the capacity of the loop is exceeded, or rehearsal is disrupted, information is lost. The rehearsal process can be disrupted in three ways (Baddeley, 2003). Articulatory suppression occurs when subvocal rehearsal is prevented by having a participant continuously repeat a sound or word, thereby interfering with the rehearsal process. The phonological similarity of words will result in similar sounding words overlapping in the rehearsal process and interfering with retention. Increased word length, the number of

syllables per word, also disrupts the rehearsal process by increasing the amount of time required for one full rehearsal cycle.

Visuospatial sketchpad. The second component of Baddeley's working memory model is the visuospatial sketchpad, another slave system. This component is responsible for processing visual and spatial information. Similar to the phonological loop, the visuospatial sketchpad is fractionated into two components (Logie, 1995). The *visual cache* is a storage component for visual information and the *inner scribe* is a more active component responsible for rehearsal of perceived movement or spatial information. Although there is substantial empirical evidence to support the visuospatial sketchpad, the fractionation of these components is less clear than those of the phonological loop (Baddeley & Logie, 1999). The visuospatial sketchpad has a limited capacity. It can retain up to four objects (Baddeley, 2003). Features of objects that are retained include color, shape, and location. Similar features, e.g. color, will overlap and disrupt retention, though different features will not (Baddeley, 2003). In summary, both slave systems are composed of a storage component and a component responsible for rehearsal or manipulation.

Central executive. The third component of Baddeley's working memory model is the central executive. Compared to the slave systems, relatively little is known about the central executive (Baddeley, 2003). It has no capacity for storing information and was originally conceptualized as a "pool of processing capacity" (Baddeley & Hitch, 1974). These processes are tapped when automatic processes or slave system rehearsal mechanisms are insufficient for handling a task. In an attempt to be more specific about the processes that comprise the central executive, Baddeley (2003) modeled the processes

that comprise the central executive after Shallice's (2002) Supervisory Attention System (SAS). Shallice (2002) proposed that the SAS is responsible for directing attention and monitoring behavior. Shallice (2002) proposes that the SAS directs attention when operations are novel rather than routine. When tasks are routine, schemas for these tasks are implemented by a process called contention scheduling. When tasks are novel, there is no available schema and the supervisory attention system must direct action by allocating more resources for new schema development and implementation. In terms of the working memory system, the central executive, like the SAS, directs more resources to the slave systems when their rehearsal mechanisms are not sufficient for a task to be completed. With the allocation of more attentional resources more complex tasks requiring manipulation of information can be completed. Based on the role of the SAS, it is clear that attention is a vital component for all functions associated with working memory according to the Baddeley (2003) model. Initial attempts at fractionating the processes attributed to the central executive have resulted in four processes: (a) focusing attention against distracting or irrelevant information, (b) dividing attention to perform two concurrent tasks, (c) switching attention between two or more simultaneous tasks, and (d) accessing information in long-term memory (Baddeley, 1996). The central executive is thought to focus, divide, and shift available resources in the working memory system (Baddeley, 2003).

Episodic buffer. The episodic buffer is a recent addition to Baddeley's (2002a) working memory model. The episodic buffer is an intermediary between the other working memory components and long-term memory. The information in episodic long-term memory is brought to conscious awareness via this component and used to provide

stored information to the slave systems. Here the information in the slave systems is assimilated with information accessed from long-term memory and new representations are created (Baddeley, 2003). Information travels bidirectionally between the slave systems and episodic long-term memory through the episodic buffer (Baddeley, 2002a, 2002b). This component also has a limited capacity, though the exact parameters have yet to be established. The functions of the episodic buffer were previously thought to be part of the central executive (Baddeley & Logie, 1999), but are now grouped as a standalone component process (Baddeley, 2003). Baddeley (2002b) hypothesizes that this component can be measured through the use of a constrained sentence span task in which the participant is required to integrate verbal, spatial, and semantic information. This span task has not yet been tested experimentally.

Cowan's Embedded Processes Model

Another multiple component memory system, though less well-evidenced, is Cowan's (1999) Embedded Processes Model. In this model there are several levels of attention or activation. According to Cowan, information enters through a brief sensory store and passes through to one of three levels of memory or activation. These levels are the (a) long-term store, (b) activated or short-term memory, and (c) focus of attention. The long-term store is all information stored but not activated. Activated memory is any information in long-term memory that is currently being processed. Focus of attention, in a similar relationship to the slave systems of Baddeley's model (2003), is controlled by the central executive. It is a heightened state of activation and brings information to conscious awareness. When incoming information is not novel or useful, the focus of attention component habituates. When information is novel, the central executive directs

the focus of attention to the novel stimuli. As information passes through the sensory store it stops at one of the levels of activation depending on how novel or significant the information. Information is retrieved from or activated in long-term memory when it is necessary for a task (Cowan, 1999). This appears similar to the integration of information from long-term memory in Baddeley's episodic buffer component except that novel information is not explicitly theorized to assimilate with old information in Cowan's (1999) model. Baddeley (2002b) has criticized this model of activation of information in long-term memory in that Cowan has been unable to specify how different features of working memory map onto these various processes in the long-term memory store. In contrast, Baddeley (2003) reports localizations of both the verbal and visuospatial components of the working memory system.

Oberauer

Oberauer and colleagues (2003) empirically derived a model of working memory with separate content and processing factors. Using structural equation modeling of 12 working memory tasks, they derived three processing factors and two content factors that comprise working memory functioning. Processing factors include (a) storage and processing, (b) supervision/switching, and (c) coordination. Content factors are verbal-numerical content and visual-spatial content. Storage and processing is defined as the ability to simultaneously store and process information. Oberauer and colleagues indicate that storage and processing are separate processes in the working memory system, but that working memory tasks by definition require both processes thereby comprising one factor rather than two separate factors. This model parallels Baddeley's (2003) model in terms of the fractionated central executive processes of dual-task coordination and task

switching, the storage processes of the slave systems, and the separate verbal and visuospatial processes.

Unitary Models

Daneman and Carpenter

Daneman and Carpenter (1980) explain working memory in terms of general capacity that is allocated between two functions: storage and processing. When completing a working memory task that requires both storage and processing, the capacity must be divided to complete both. They developed a reading span task to measure both processes and their interrelationship. In this reading span task, the participant is required to read a series of sentences and remember the last word of each sentence. With each sentence the reader has to divide their working memory capacity between processing the current sentence and storing the last words from previous sentences. This understanding of working memory, though unitary, also fits into Baddeley's (2003) framework by understanding that storage, or slave system functioning, and processing, or additional attentional resources allocated by the central executive, are components of working memory.

Engle

Another unitary theory of working memory functioning, proposed by Engle and colleagues is entirely dependent on attentional capacity rather than functioning of component processes. Engle (2002) argues that working memory capacity is not about memory itself. He concludes that working memory capacity is about using attention to maintain or suppress information. He argues that removing common memory variance,

variance from tasks requiring only simple memory processes such as rehearsal and chunking, results in isolation of executive attention.

Though Engle and colleagues advocate for a non-domain specific working memory system, they are actually referring to a non-domain specific executive component. It is the functioning of this executive component that they argue is working memory capacity (Kane et al., 2004). Consistent with Baddeley (2003), and Oberauer and colleagues (2003), they argue that storage is domain specific; however, the executive component operates across multiple domains, i.e. verbal and spatial. This is parallel to the central executive concept in other models (Baddeley, 2003; Cowan, 1999) in that it is an executive control mechanism that relates to multiple domains of processing.

This hypothesis that working memory capacity, or executive attention as it is called by Engle (2002), is non-domain specific was verified through a comparison of working memory capacity task performance and short-term memory task performance on both verbal and visuospatial domain tasks (Kane et al., 2004). Working memory capacity tasks involved concurrent processing while maintaining target stimuli. Short-term memory tasks were simple span tasks without concurrent processing of other information. Results indicate that working memory capacity tasks across domains correlated higher with each other as compared to short-term memory task correlations across domains. These results were interpreted to indicate that working memory capacity tasks were more domain general than short-term memory tasks.

This domain general executive concept was further confirmed through confirmatory factor analysis in which a one factor model and a two factor model, i.e. verbal and spatial factors, resulted in approximately equivalent model fits. Based on

parsimony, the single factor is a better explanation of the results supporting that working memory capacity, or executive attention, is best explained through a non-domain specific model (Kane et al., 2004). It was also reported that verbal and spatial working memory capacity tasks shared 75 to 80 percent of their variance. This also indicates that a majority of the processes involved in these tasks are not domain specific. In contrast, the verbal and spatial short-term memory tasks shared only 40 percent of their variance indicating that these tasks are more reliant on domain specific processes. These findings were found despite Kane and colleagues (2004) report that the short-term memory tasks used in the experiment were more closely related in terms of processing demands and testing procedures than were the working memory capacity tasks. The finding that working memory capacity tasks were less similar than short-term memory tasks and were still found to be more highly correlated indicates strong evidence for non-domain specific executive component, similar to the central executive of the multicomponent models (Kane et al., 2004).

Despite the high degree of shared variance between working memory tasks, a four factor model, working memory capacity verbal, working memory capacity spatial, short-term memory verbal, and short-term memory spatial, was the best fit model indicating that while domains are less important for working memory capacity tasks, the domain differences on tasks are not negligible (Kane et al., 2004). These results, rather than supporting Engle's (2002) claim of unitary working memory, support Baddeley's (2003) multicomponent model including a distinct central executive with separate verbal and visuospatial processes. Though Engle (2002) discusses working memory as unitary, his model and subsequent research truly parallel the functioning of the central executive

component of Baddeley's (2003) model. Results of this line of research continue to support content specific short-term processes or slave systems and a domain general executive system like the central executive.

Support for Multicomponent Models

One consistent discrepancy in the working memory literature is between the terms short-term memory (STM) and working memory (WM). Evidence supporting this distinction also provides support for the multicomponent conception of working memory. In some studies, these terms are used interchangeably; however, in most of the literature, short-term memory is indicated to be a lower order process of the working memory system. Engle (2002) argues that measures of working memory capacity reflect memory processes with the addition of requiring executive attention, whereas short-term memory tasks only require simple memory processes such as chunking and rehearsal. This is consistent with results of a study by Kail and Hall (2001) evaluating working memory in children. Kail and Hall (2001) discuss WM as STM plus additional attentional resources required to complete more complex tasks. This claim is based on Cowan's (1999) proposal that attention is needed to keep memories in an active state.

Based on confirmatory factor analysis, Kail and Hall (2001) propose that STM and WM are distinguishable but not independent factors. Though tasks that measured lower cognitive processes such as rehearsal loaded on a separate factor than tasks that tapped higher processes such as dual processing, the two factors labeled STM and WM were moderately correlated (.32 to .36). These results indicate that WM and STM share processes. Based on the WM as STM plus attentional resources understanding, it appears that the shared variance between the two factors may be attributable to a single WM

system that includes both lower (rehearsal) and higher processes (manipulation) based on the task demand. This two factor model was found in a sample of children as early as elementary age (Kail & Hall, 2001). These results indicate that one component is not sufficient for description of processes involved in the working memory system.

Other researchers have investigated the difference between STM and WM using factor analysis. Reynolds (1997) explored the different factor loadings of forward and backward digit span tasks. Forward digit tasks require simple recall, whereas backward digit tasks require additional complex processes. Reynolds showed that these tasks have separate factor loadings and should therefore not be combined when interpreting test results. If these two tasks are combined the distinctiveness and clinical utility of the two processes are lost. Reynolds found that 25 to 30% of all normal children have at least a 1 standard deviation difference between forward and backward digit tasks. The difference between forward and backward digit tasks appears to represent the same distinction used by Kail and Hall (2001) for STM and WM and the distinction between storage and processing made by Oberauer and colleagues (2003) and Daneman and Carpenter (1980). Results of these studies examining the differences between storage or short-term memory processes and processing or working memory processes lends support to the use of a multicomponent model, such as Baddeley's (2003), for comprehensive understanding working memory function.

Support for the components of Baddeley's (2003) model has also been found in child samples. Alloway and colleagues (2004) tested various models of working memory including a single component model and a multicomponent model of working memory in relation to other cognitive process such as phonological awareness and nonverbal ability

in children between the ages of 4 and 6. Using structural equation modeling, the model that best fit the data was a five factor model consisting of the central executive, episodic buffer, phonological loop, phonological awareness, and nonverbal ability. The visuospatial sketchpad was not assessed in this experiment because all memory measures were verbal. This model, in addition to providing support for the multicomponent working memory model also indicates the presence of a strong relationship between the phonological loop and the central executive. The researchers conclude that this is the result of verbal span tasks relying on the phonological loop for storage and the central executive for processing (Alloway et al., 2004).

Additional empirical evidence for acceptance of a multicomponent model is found in imaging studies of working memory task performance. Owen and colleagues (1999) found that blood flow to various areas of the frontal cortex differed with working memory task demands. On a forward spatial span task that required only maintenance, or storage, of information, blood flow increased to the mid-ventrolateral frontal cortex. When participants completed a 2-back memory task requiring both maintenance, remembering a series of numbers, and manipulation of information, comparing each number to the previously presented numbers and deciding whether they are the same or different, blood flow increased to both the mid-ventrolateral frontal cortex and the mid-dorsolateral prefrontal cortex (Owen et al., 1999). Though this study had a small sample size of five participants, results provide some evidence for differences in brain blood flow that is consistent with factor analytic findings of Reynolds (1997), Alloway and colleagues (2004), and Oberauer and colleagues (2003). Each of these studies indicates that working memory is a combination of lower storage or maintenance processes and

higher-level executive processes as advocated by proponents of multicomponent working memory models.

The differences in factor loadings for tasks with different processing demands exhibited by Kail and Hall (2001) and Reynolds (1997) in conjunction with processing/storage distinction and multiple processing and content factors of Oberauer and colleagues (2003) appear to justify conceptualizing working memory as multicomponent rather than unitary. In addition, each of the proposed unitary and multicomponent models easily fit into the framework of Baddeley's (2003) model. As previously noted, both Cowan's (1999) and Baddeley's (2003) models share a central executive that serves to direct attentional resources. Oberauer and colleagues' (2003) multiple processing factors are similar to the proposed fractionated processes of the central executive (Baddeley, 1996). Engle's (2002) concept of executive attention parallels Baddeley's (2003) central executive in that both implicate control of attention as necessary for direction and completion of complex working memory tasks. Based on the similarities among the multicomponent models and the amount of empirical support, Baddeley's (2003) model of working memory will be the model on which the current research is based.

Fractionating the Central Executive

As the components of the working memory model have been firmly established in the literature, Baddeley (1996) has begun to focus specifically on the central executive component. This component has historically been the least specific component of the model. Researchers began to fractionate it into several processes. The primary research paradigm used in these attempts to fractionate the central executive is a dual task

procedure. The idea behind dual task procedures is if two tasks can be performed simultaneously without a decrease in performance as compared to performing the tasks alone, then the tasks are thought to be the result of independent processes (Duff, 2000).

Fractionation of the central executive has been carried out almost exclusively in Alzheimer's patient populations because of the well-evidenced deficit in executive control in this population (Baddeley, 2002a). When asked to perform concurrent tasks participants with Alzheimer's evidenced a more marked decline in performance as compared to their single task performance and performance of normal and age-matched controls indicating that executive control to divide resources, a process attributed to the central executive, is required for dual task performance (Baddeley et al., 2001; Baddeley et al., 1986). Switching has also been evaluated using a dual task paradigm (Baddeley, 2001). Weaker results for central executive involvement in task switching were found as compared to dividing resources (Baddeley, 2002a).

Duff (2000) investigated the distinction between storage and processing tasks to determine if the central executive has involvement with storage or processing of information on concurrent verbal and visuospatial tasks. In the first experiment, participants were required to store a series of numbers alone, a series of locations of a grid alone, and store the numbers and their location on the grid at the same time. Dual task scores were then subtracted from the single task scores to determine the difference score. The result that performing both tasks simultaneously does not result in interference indicates that storage of verbal and visuospatial information are separate processes. Completing these verbal and visuospatial tasks simultaneously was modeled after initial experiments that led to development of the original Baddeley and Hitch (1974)

multicomponent model of working memory. Duff (2000) concluded from this experiment that the coordination mechanism of the central executive is not required for multiple storage tasks. The slave systems therefore operate independently when conducting storage tasks.

Duff (2000) then conducted a similar dual task experiment using tasks requiring processing rather than storage to investigate central executive involvement in tasks requiring processing. The verbal task required subjects to listen to a series of words and nonwords and repeat the real words. The visual task required participants to discriminate between targets and non-targets on a computer screen by clicking on the targets with a mouse. The dual task required participants to perform the verbal and visual tasks concurrently. Results of this experiment indicated a significant decline in performance when comparing single and dual task on the visual task, but non-significant decline in performance between single and dual task performance on the verbal task. The researchers conclude from these results that dual-task processing is attributed to a shared process as evidenced by the decline in performance on the visual processing task when performed concurrently with the verbal processing task. They suggest that the non-significant results of the difference between single and dual task performance on the verbal processing task indicates that participants focused more resources on the verbal task at the expense of their performance on the visual task when completing the dual task procedure (Duff, 2000). Results of both of these experiments are consistent with the Baddeley (2003) model of working memory in that storage functions carried out by the slave systems operate independently, or do not share resources; whereas, when processing tasks require the coordination function of the central executive performance

declines because of the limited resources that must be shared when processing. This is also consistent with Oberauer and colleagues' (2003) research in which factor analysis resulted in two factors in analysis on multiple working memory tasks: one for processing and one for storage.

Though it is common in neuropsychology to separate cognitive functioning from brain localization for research purposes (Baddeley, 2002a), there is imaging data to support the fractionation of the central executive (Collette & Van der Linden, 2002). In these imaging experiments, participants were first required to perform tasks requiring processes attributed to the slave systems in order to differentiate these brain activations from those of the central executive. Tasks involving manipulating, updating, inhibition, and shifting were found to lead to brain activation in both prefrontal and parietal areas. Some brain areas appeared to activate for general executive tasks, whereas others appear to activate for more specific cognitive tasks (Collette & Van der Linden, 2002). This differential activation based on task demands supports the fractionation of the central executive in that different processes lead to differential brain activation though some brain areas are involved in all tasks of the central executive.

Baddeley (1996, 2002a) has suggested several fractionated processes of the central executive through the use of experimental studies in Alzheimer's patients. These are coordination of simultaneous tasks, shifting between tasks, random generation, interfacing with long-term memory, and activation of long-term memory. Two apparent themes in the processes suggested by Baddeley as components of the central executive are control of attention and control of retrieval from long-term memory. Building upon the research of Baddeley (1996, 2002a; Baddeley et al., 1986), Zoelch and colleagues

(2005) examined bivariate correlational relationships between several working memory measures to distinguish these central executive subprocesses in a child sample. Based on the correlational relationships and Baddeley's research, they concluded that four subprocesses comprised the central executive. The subprocesses were named: (a) selective attention and inhibition processes, (b) the coordination of simultaneous tasks and task switching, (c) the control of encoding and retrieval strategies, and (d) retrieval of information from long-term memory.

They further attempted to validate the subprocesses by examining differences in effects size for each working memory measure across the age span (Zoelch et al., 2005). To determine these developmental differences, the researchers compared effect sizes of the sample with and without each age group. Great differences in effect size indicated an effect of age for that measure and the related process. Zoelch and colleagues (2005) examined which working memory measures had similar patterns of age effects and found that these patterns were consistent with the pattern of bivariate correlations among the working memory measures. Based on the pattern of age effects found on the working memory measures and the correlational relationships of those measures, Zoelch and colleagues (2005) concluded that they effectively measured all four components of the central executive and that each of these processes has a distinct developmental trajectory.

There are problems with researching the fractionated components of the central executive. These difficulties are demonstrated by the Zoelch and colleagues (2005) study. Executive tasks are typically not single process measures. Measures of executive functioning typically involve multiple executive processes and/or other cognitive processes outside the domain of the executive including those processes attributed to the

slave systems (Collette & Van der Linden, 2002). Zoelch and colleagues (2005) utilized experimental working memory measures without established construct validity. In addition, they did not sufficiently triangulate the task demands of their measures to isolate the neuropsychological processes under investigation. Because the working memory tasks shared task demands, the correlational relationships utilized to form the experimenters conclusions cannot with certainty be attributed to central executive variance. In addition, Zoelch and colleagues (2005) did not empirically establish the central executive subprocesses that the bivariate correlations are said to have confirmed. Despite these methodological issues, results of this study further validate the themes of control of attention and control of retrieval found in Baddeley's investigation of central executive processes (Baddeley, 1996, 2002a) and then extend these themes to a child population.

In an attempt to evaluate the relationship between the slave systems and the central executive, a dual task paradigm was used by Kondo and Osaka (2004). Their goal was to examine whether the phonological loop and the visuospatial sketchpad are equally susceptible to the control functions of the central executive. Separate verbal and visuospatial storage tasks were administered to participants as primary control measures. Other secondary tasks were then added to those primary tasks to determine the degree of interference of central executive functions on the primary tasks. These secondary tasks included single-digit addition, digit-carrying operation, and digit reading. A limitation of this study is that the visuospatial task asked participants to remember locations of numbers. As numbers are encoded verbally it is unlikely that this is a purely visuospatial task. In an attempt to prove that this task was visuospatial, the researchers compared

results of this task with that of a spatial span task and found significant correlations (Kondo & Osaka, 2004); however, this does not rule out the use of verbal encoding as a strategy used by participants. It is also questionable as to why the experimenters chose automatized tasks as their secondary tasks. Digit reading, simple, and even the more difficult arithmetic tasks chosen to interfere with the primary tasks are all automatized and therefore do not have the cognitive demands associated with novel tasks typically used in dual task paradigms. Despite these limitations, Kondo and Osaka (2004) did find that performance on the primary tasks was affected by the secondary tasks. Digit reading had a greater effect on the verbal task performance. It also had a small effect on the visuospatial task. Easy addition (single digit) had a greater effect on visuospatial performance than verbal performance. The difficult addition task appeared to affect verbal and visuospatial performance equally. From these results, the authors conclude that there is asymmetry in the degree of involvement of the central executive with the slave systems.

Loisy and Roulin (2003) created a unique task to evaluate the coordination function of the central executive. Participants were required to remember a sequence of words and the location of the words on the grid. Recall of the words, their location, or words and their location were all used in a randomized fashion within the same task. This requires the participant to encode both visuospatial and verbal information at the same time thereby utilizing the central executive for coordination of both slave systems operating simultaneously. Interference tasks are also completed during retention intervals of the double-stimuli task. These interference tasks include no interference, articulatory suppression, Moar box tracking i.e. pressing keys on a five by five grid throughout the

retention interval, and standing balance position. Articulatory suppression interfered with word recall but not location recall. Both Moar box and standing balance interference tasks interfered with location recall but did not interfere with word recall. There was a significant decrease in recall performance between single tasks and the dual task conditions regardless of the interference condition. Comparisons of the interference tasks indicate that there is no difference between no interference and standing balance interference. There is also no difference between articulatory suppression and Moar box interference. There is a significant difference between these two categories of interference. Loisy and Roulin (2003) argue that this is evident of central executive involvement because the decrease in performance related to interference on the dual task recall is related to task demands rather than to the type of interference.

Models of Attention as Models for the Central Executive

Mirsky

As the central executive is described as an attentional control component of the working memory system and there is inconsistency and a lack of empirical confirmation of the identified fractionated processes of the central executive (Baddeley, 1996, 2002a; Baddeley, et al., 1986; Zoelch et al., 2005), it is necessary to look beyond the working memory literature into the attention literature to obtain a comprehensive understanding of processes that potentially comprise the central executive. Similar to Baddeley's (2002a) argument that the central executive must be fractionated into component processes in order to comprehensively understand the working memory system, Mirsky and colleagues (1991) argue that attention should be fractionated into multiple types of attention. They indicate that considering attention as a unitary construct is not clinically

or empirically useful and suggest four types of attention. These types are: (a) focus/execute, defined as the ability to selectively attend to information; (b) shift, defined as the ability to change attentive focus; (c) sustain, defined as the ability to maintain focus or alertness over time; and (d) encode, defined as recall and mental manipulation of information. These types of attention are the result of a factor analysis of 11 measures of attention. This same factor structure was found in both child and adult samples. Though the first three factors are clearly different types of attention, the fourth factor appears to reflect working memory rather than a fourth type of attention. The definition for the encode factor, recall and mental manipulation of information, is consistent with the definition of working memory (e.g. Baddeley, 2003). In addition, the measures that loaded on that factor, digits forward and arithmetic, have been shown to load on factors labeled working memory (Wechsler, 2003). The authors (Mirsky et al., 1991) also report that in follow-up confirmatory factor analyses conducted by other researchers (e.g. Steinhauer et al., 1991), the first three factors were consistently found, whereas the fourth was not.

Posner

Posner and Raichle (1994) suggest another, though similar, theory of the components of attention. These components include: (a) alerting, defined as suppressing background information and preparing to act by inhibiting irrelevant activity; (b) orienting, defined as initiating use of specific cognitive resources for a task; (c) and executive control or executive attention, defined as coordinating multiple neural processes to complete a specific goal. Each of these component processes is based in a distinct neural system. Executive attention, for example, is primarily localized in the

anterior cingulate cortex with frontal lobe and basal ganglia involvement. Swanson and colleagues (1998) relate the terms used for attention in Posner and Raichle (1994) to more common terms used in other attention research. In each case the network function described by Posner is related to a cognitive process measured in the attention literature. The alerting process sets the occasion for sustained attention in that a maintained state of alertness is necessary for vigilance (Swanson et al., 1998). Alerting is therefore the neural process that results in the cognitive process sustained attention. A similar relationship exists between orienting (Posner & Raichle, 1994) and selective attention. Swanson and colleagues (1998) suggest that the orienting process is a response to the internal and external cues required for effective selective attention and implementation of appropriate processing. The executive attention network is related to the coordination of multiple cognitive processes or divided attention (Swanson et al., 1998). In a discussion of Posner's work, Mirsky and colleagues (1991) point out the similarity between Posner's orient-detect and maintaining vigilance and their own focus/execute and sustain concepts.

Factor analytic support

Both Mirsky and colleagues (1991) and Posner and Raichle's (1994) models include sustained attention, selective attention, and some executive attention component whether it is coordination or shifting attention. These same processes have been found to be represented in results of factor analysis of multiple measures thought to measure attention. In development of their Test of Everyday Attention for Children (TEA-Ch), Manly and colleagues (2001) conducted a confirmatory factor analysis of nine subtests designed to measure different types of attention. The best fit model for their data was a three factor model with selective attention, attentional control/switching, and sustained

attention. Though dual-task measures for divided attention were included in the battery, these subtests were found to load on the sustained attention factor. This is consistent with results of a similar confirmatory factor analysis conducted in an adult population (Robertson et al., 1996) in which a three factor model of attention was derived with factors labeled selective attention, attentional control/switching, and sustained attention. Divided attention tasks were found to load on the sustained attention factor in this study as well. Results of both of these studies (Manly et al., 2001; Robertson et al., 1996) and additional confirmatory factor analyses on younger (ages 6 to 10.91) and older (ages 10.92 to 16) children (Manly et al., 2001) indicate that this factor structure is stable across the age span beginning as young as age 6. Additional support for these types of attention as separate processes is found in a study by Tsal and colleagues (2005) in which measures of selective attention, sustained attention, and executive attention did not significantly correlate in an ADHD population. The highest correlation was between sustained attention and executive attention ($r = -.221$) indicating that these two constructs only share four percent of their total task variance. These results in conjunction with factor analytic results of the TEA-Ch instrument (Manly et al., 2001) indicate that sustained attention, selective attention, and executive or shifting attention are separate but related processes.

Baddeley's Fractionated Central Executive and Attention Models

Based on the inconsistency and lack of empirical confirmation in the working memory literature as to the specific fractionated processes of the central executive (Baddeley, 1996, 2002a; Baddeley et al., 1986; Zoelch et al., 2005), the consistency of the fractionated processes of attention identified in the attention literature (Manly et al.,

2001; Mirsky et al., 1991; Posner & Raichle, 1994; Robertson et al., 1996; Swanson et al., 1998; Tsal, Shalev, & Mevorach, 2005), and Baddeley's conceptualization of the central executive as an attentional control system (Baddeley, 2003), the following components of attention will be included in the current model of the central executive: selective attention/inhibition, sustained attention, and shifting attention (Manly et al., 2001; Mirsky et al., 1991; Posner & Raichle, 1994; Robertson et al., 1996; Swanson et al., 1998; Tsal, Shalev, & Mevorach, 2005). These processes are similar to those found in the working memory literature; however, they have greater empirical support and will therefore be included in the current model.

Lezak and colleagues (2004) define selective attention as the capacity to focus on important stimuli while suppressing awareness of competing distractions. Barkley (1997) indicates that three processes comprise inhibition: (a) inhibition of a prepotent response, (b) stopping an ongoing response, and (c) protecting from disruption by competing stimuli. As the definition of selective attention is consistent with Barkley's (1997) third component of inhibition, selective attention and inhibition processes will be discussed as a single construct.

As control of retrieval from long-term memory is a consistent theme of the central executive identified in the working memory literature (Baddeley, 2002a, 2003; Zoelch et al., 2005) it will also be included in the model. Therefore, the model of the central executive utilized in the current study will include four component processes: (a) selective attention/inhibition, (b) sustained attention, (c) shifting attention, and (d) control of retrieval from long-term memory. Selective attention/inhibition is defined as the capacity to focus on important stimuli while suppressing irrelevant stimuli (Barkley,

1997; Lezak et al., 2004; Mirsky et al., 1991). Sustained attention is defined as the capacity to maintain attention over time (Lezak et al., 2004; Mirsky et al., 1991). Shifting attention is defined as the ability to change focus in a flexible manner (Lezak et al., 2004; Mirsky et al., 1991).

Gender Differences on EF Measures

Manly and colleagues (2001) compared performance of 146 boys and 147 girls, ages 6 to 16, on all subtests of the Test of Everyday Attention for Children (TEA-Ch), a measure designed to measure multiple types of attention including sustained attention, selective attention, and executive control. Results of this study indicated that boys and girls did not perform differently on any of the nine subtests with the exception of one executive control subtest requiring the children to shift between counting forwards and backwards based on visual stimulus indicating when to change. Boys and girls did not differ on measures of sustained attention or selective attention. Boys and girls also did not differ on the other cognitive control measure in the battery, requiring participants to say words that are the opposite of presented stimuli. Results of this study appear to indicate that boys and girls, ages 6 to 16, do not differ on measures of attention. Tsal and colleagues (2005) examined gender differences within the ADHD population. Boys and girls did not differ on measures of executive attention; however, boys made significantly more commission and omission errors on a continuous performance test indicating that group differences in gender on measures of sustained and selective attention do occur across genders, though not consistently. Though there is some evidence of gender differences on omission and commission errors, the measures to be used in the current study use age and gender based norms for these variables.

ATTENTION DEFICIT/ HYPERACTIVITY DISORDER

Diagnostic Criteria

Children with Attention-Deficit/ Hyperactivity Disorder (ADHD) are known to have deficits in multiple areas of executive functioning including working memory (Barkley, 1997; Shallice et al., 2002). ADHD is a behavior disorder typically diagnosed in childhood. According to the Diagnostic and Statistical Manual – Fourth Edition, Text Revision (American Psychiatric Association, 2000), symptoms of this disorder fall into three subtypes. The first subtype is inattention. The second subtype is hyperactive-impulsive. The third subtype is combined hyperactive/impulsive and inattention symptoms. Inattention symptoms include making careless mistakes, difficulty sustaining attention, not listening, not following through on instruction, difficulty organizing tasks, reluctance to engage in tasks requiring sustained effort, losing things, being easily distraction by non-relevant stimuli, and forgetfulness. Hyperactive symptoms include fidgeting, frequent leaving of seat in the classroom, running or climbing when inappropriate, difficulty staying quiet in leisure activities, frequently being on the go, and talking excessively. Symptoms of impulsivity include blurting out answers before questions have been completed, difficulty waiting their turn, and butting into conversations or games (American Psychiatric Association, 2000).

These categories of symptoms provide guidelines for diagnosing ADHD and the associated subtypes. Children that have 6 symptoms in the inattention category are diagnosed as ADHD Predominantly Inattentive Type. Children with 6 symptoms only in the hyperactive and impulsive categories are diagnosed as ADHD Predominantly Hyperactive-Impulsive Type. Those children with at least 6 symptoms in both domains

are diagnosed as ADHD Combined Type (American Psychiatric Association, 2000). For diagnosis to occur, symptoms must be present before the age of seven, last for 6 months, be present in two or more settings, and not be better accounted for by another disorder. Disorders that are commonly comorbid with ADHD are depression, anxiety, oppositional defiant disorder, conduct disorder, and learning disability (Barkley, 2003).

Prevalence

Prevalence rates of ADHD vary substantially depending on diagnostic procedures used. Rates are estimated to be 3 to 7 percent of the general population (Barkley, 2006). Highest prevalence rates are found when teachers' ratings are the sole criteria. Lower rates result when multiple raters are required to agree on diagnosis before it is made (Barkley, 2003). Prevalence rates also differ based on diagnostic criteria. In a sample of 484 first-grade students, Guardiola and colleagues (2000) compared diagnostic rates using DSM-IV criteria versus DSM-IV and neuropsychological testing criteria. Results indicated a 35% rate of diagnosis with DSM-IV criteria and a 4% diagnostic rate with neuropsychological criteria added (Guardiola, Fuchs, & Rotta, 2000).

Prevalence rates are negatively correlated with the age of children with the diagnosis becoming less frequent as children grow older (Barkley, 2003). There is a higher prevalence of the disorder in males than females with approximately three times as many males having the diagnosis (Barkley, 2006). Prevalence rates also increase in lower socioeconomic status groups and groups with more family dysfunction. It is interesting to note, however, that these environmental factors no longer affect prevalence when comorbid disorders are taken into account (Barkley, 2003). Socio-economic status differences are also eliminated if all raters, such as parents, teachers, and physicians,

agree on the diagnosis (Szatmari, 1992). This elimination of differences in prevalence rates suggests that differences in prevalence due to environmental factors are a result of the influence of environment on comorbid disorders such as anxiety and depression rather than environmental factors leading to ADHD. Cultural differences in prevalence rates for ADHD are attributed to differing expectations for behavior (Barkley, 2003). For this reason, environmental influences are not considered an essential part of the development of the disorder, though they can contribute to the positive or negative outcome of the disorder.

Etiology

Genetics

Genetics have been consistently linked to development of ADHD. Biederman and colleagues have conducted several studies in which they indicate prevalence rates of ADHD are higher within families than between. In one study, they found 10 to 35 percent of family members of a child with ADHD are likely to have the disorder (Biederman, Faraone, & Lapey, 1992). In another study, they found that children of a parent with ADHD have a 57 percent risk of having the disorder (Biederman et al., 1995). Faraone and colleagues (2000) also found that relatives of girls with ADHD had equivalent prevalence rates of relatives of boys with the disorder. It has also been found that correlations between monozygotic twins having the disorder are larger than those for dizygotic twin pairs (Hudziak et al., 2005). All of this evidence indicates that genetics play a large part in the development of ADHD.

Neuroanatomy

Neurological factors also contribute to the development of this disorder. It has been found that children with ADHD have smaller total brain mass as well as smaller superior prefrontal areas, smaller cerebellum, and less corpus collosum area. These patterns of differences in size did not differ between males and females (Hill et al., 2003). In a number of imaging studies it has been shown that various brain regions are activated differently between individuals with ADHD and controls. The frontal lobe of the brain is often discussed in children with ADHD because of the associated executive functions deficits. Neuropsychological deficits associated with ADHD are very similar to those found in patients with frontal lobe damage (Shue & Douglas, 1992; Shallice et al., 2002). This similarity indicates that the frontal cortex plays an important part in the neuropsychological deficits associated with ADHD. As working memory is thought to be localized primarily in the dorsolateral prefrontal cortex (Baddeley, 2003), it is likely that differences in frontal cortex functioning may be related to working memory deficits in children with ADHD.

Models of Executive Dysfunction in ADHD

It has been suggested by Shue and Douglas (1992) that it is useful for both theory and clinical use to consider ADHD as a disorder of higher-order neuropsychological processing. Seidman and colleagues (2001) found executive impairment in children with ADHD even after controlling for differences in intelligence quotient. In a meta-analysis of 83 research studies of children with ADHD and controls, Willcutt and colleagues (2005) found that children with ADHD performed significantly worse than controls on 13 measures of executive functions. Frazier and colleagues (2004) found that effect sizes

between ADHD and control children were larger for executive measures for non-executive neuropsychological measures. It has also been found that these deficits in executive functions are consistent with regard to age and gender within the ADHD population (Seidman et al., 2005). Several models of executive functioning in children with ADHD have been proposed. Each model will be explained and examined in terms of theoretical and empirical support.

Barkley

A widely accepted model of executive functioning in children with ADHD proposed by Barkley (1997) implicates behavioral inhibition as the primary deficit that prohibits adequate functioning of other areas of executive functioning. This model explains that, in relation to executive functions, behavioral inhibition allows delays in action that set the occasion for their performance and protect their performance from interference (Barkley, 1997). It is during this delay in action that other executive processes such as problem solving and working memory take place. Once the dominant, or prepotent response is inhibited, the executive functions aid the individual in selecting the appropriate behavior. Without the ability to inhibit behavior, other executive processes that operate within this delay cannot properly occur (Barkley, 1997).

The other areas of executive functioning implicated by Barkley (1997) as impaired because of dysfunctional behavioral inhibition include nonverbal working memory, verbal working memory or internalization of speech, self-regulation of affect/arousal/motivation, and reconstitution. Barkley defines nonverbal working memory as covert self-direction of behavior and sensory experiences (Barkley, 1997). This includes seeing and hearing within the self. Behaviors listed under the umbrella of

nonverbal working memory include imitation of complex behavior sequences, retrospective and prospective memory function, and sense of time. These functions are thought to be localized in the dorsolateral prefrontal cortex and are related to the visuospatial sketchpad in Baddeley's model of working memory (Barkley, 1997).

Verbal working memory, similar to the articulatory loop described in Baddeley's model of working memory (Barkley, 1997) is described as the ability to have a conversation with oneself internally. Barkley (1997) suggests this function is necessary for self-direction of behavior. Resulting behaviors of verbal working memory include description, reflection, self-questioning, problem-solving, and moral reasoning (Barkley, 1997).

Self-regulation of affect, arousal, and motivation (Barkley, 1997) is similar to intrinsic motivation. Related behaviors include self-regulation of affect, perspective taking, self-motivation, and self-arousal toward goal directed action (Barkley, 1997). Behavioral inhibition, according to Barkley, allows an individual the time to regulate their affect prior to presenting it to others.

Reconstitution refers to analysis and synthesis of behavior (Barkley, 1997). Synthesis is the combination of previously learned behaviors with new behaviors. Analysis is dividing up new behaviors into categories and subcategories (Barkley, 1997). Related processes to reconstitution include verbal and behavioral fluency and rule-directed behavioral creativity. Barkley argues that dysfunctional behavior inhibition does not allow the time needed for analysis and synthesis of behavior because all responses are impulsive in nature (Barkley, 1997).

Barkley argues that the combination of behavioral inhibition and the four other areas mentioned, when functioning properly, allow behavior to be purposive, goal oriented, and intentional. When the system is not functioning properly, as in the case of ADHD, these types of behavior are not carried out effectively (Barkley, 1997).

Other researchers have reportedly found support for this model. In a longitudinal study of children with ADHD from age 5 to 8, it was found that inhibition performance in preschool was predictive of executive functions performance and ADHD symptoms at school age (Berlin, Bohlin, & Rydell, 2003). Berlin and colleagues (2003) suggest that this supports the primacy of behavioral inhibition; however, an alternative explanation, not addressed by Berlin and colleagues (2003), is that the predictive nature of behavioral inhibition performance in preschool is an indication of consistent executive dysfunction across the developmental sequence.

In another study by Berlin and colleagues (2004), boys, ages 7 to 10 years, with ADHD and age, ethnicity matched controls were compared on measures of the areas of executive functions implicated in Barkley's model. Though group differences were found in all areas of Barkley's model except non-verbal working memory, only inhibition and self-regulation contributed unique variance to prediction of ADHD diagnostic status in logistic regression analyses. Verbal working memory and reconstitution did not contribute significant amounts of unique variance to diagnostic status (Berlin et al., 2004). The authors conclude that these results support Barkley's model. Though these results and results of their previous study (Berlin et al., 2003) do not provide support for the hierarchical nature of Barkley's model, they do indicate that elements in Barkley's (1997) model are key areas of executive dysfunction in children with ADHD.

Though Barkley advocates for inhibition as the source of all executive dysfunction in ADHD, including working memory performance, Valera and colleagues (2005) found that there was less cortical activation in the cerebellum, occipital cortex, and right prefrontal cortex on an n-back working memory task. These differences were found even after controlling for activation on an X-vigilance task. This indicates that the differences in activation on the working memory task were not solely the result of inhibition. Though the ADHD and control adults were found to have differences in activation during the working memory measure, their performance on this task did not differ. Imaging studies have also shown that there are not differences in cortical activation between children with ADHD and controls on tasks of inhibition (Schulz et al., 2005). Though Barkley (1997) states that inhibition is the primary executive deficit that results in decreased working memory performance, results of this imaging study do not support this idea. Also, the hierarchical nature of the model and associated inter-relationships among executive functions have yet to be established empirically.

Nigg

Nigg's integrative theory of executive dysfunction in ADHD (Nigg & Casey, 2005) is based on the following definition of cognitive control: "the ability to suppress inappropriate behaviors in response to contextual and temporal cues and adjust behavior accordingly" (p. 786). Nigg and Casey (2005) state that, based on neurodevelopmental differences in brain circuitry including the frontostriatal and frontocerebellar loops, children with ADHD lack this cognitive control and it therefore affects their ability to know (a) what to expect in specific situations, (b) when to expect things in specific situations, and (c) and which emotional stimulus as relevant or irrelevant to specific

situations. Because they do not identify these vital pieces of information about their environment, children with ADHD then do not make the connection between the environmental demands and appropriate behavior. This results in a lack of additional cognitive resources being allocated to selection of appropriate actions and inappropriate actions, whether cognitive or behavioral, are then implemented.

Nigg and Casey (2005) link this failure to make connections and allocate resources to both inhibition and set shifting. An inhibition failure is identified in that behaviors that are inappropriate based on environmental cues are not inhibited. Because of this lack of inhibition, switching of attention or behavior change cannot occur. Nigg and Casey (2005) then hypothesize that this lack of inhibition and shifting result in poor working memory performance because working memory tasks require the child to hold multiple goals and adjust their performance based on task demands.

Brown

Similar to Nigg and Casey (2005), Brown (2006) disagrees with Barkley that inhibition is the primary executive function that results in all other executive dysfunction. Brown hypothesizes that six areas of executive functions are altered in ADHD. These areas are: (a) activation, defined as organizing, prioritizing, and activating to a task; (b) focus, defined as focusing, sustaining, and shifting attention to tasks; (c) effort, defined as regulating alertness, sustaining effort, and processing speed; (d) emotion, defined as managing frustration and regulating emotions; (e) memory, defined as utilizing working memory and accessing recall; and (f) action, defined as monitoring and self-regulating action. Brown (2006) points out that rather than being the primary deficit, inhibition interacts and is interdependent with the other executive functions. To indicate that one

area of executive functioning is central to executive dysfunction is, according to Brown (2006), overly reductionistic in that it simplifies a complex, inter-related system of cognitive processing down to one key process.

Sergeant

Sergeant (2000) conceptualizes cognitive processing in children with ADHD as a three-tiered model. These tiers are designed to account for what Sergeant calls bottom-up and top-down processes. Top-down processing involves higher cognitive processes affecting lower cognitive processes and bottom-up processing involves lower cognitive processes affecting higher cognitive processes. The first tier is composed of stages of information processing including encoding, search, decision, and motor organization. These are the lower cognitive processes that Sergeant proposes may affect processes in higher tiers of the model. The second tier is made up of what Sergeant (2000) refers to as energetic pools. The three pools in the model are effort, arousal, and activation. Effort is defined as necessary energy to meet task demands. Arousal is defined as time allotted for stimulus processing. Activation is defined as changes in physiological activity. This second tier is Sergeant's intermediary between top-down and bottom-up processing (Sergeant et al., 2003). Each of these energetic pools can affect both higher and lower cognitive processes. Sergeant (2000) also includes a third tier called management/executive function which he indicates is responsible for planning, monitoring, detecting errors, and correcting errors. These are the higher processes that have a top-down effect on tier one processes.

Sergeant's model is not proposed to explain all executive dysfunction in children with ADHD as Barkley (1997a), Nigg and Casey (2005), and Brown (2006) have

attempted. Rather, it is an attempt at explaining the mechanism by which impulsive behaviors occur. Though executive functions are included as part of the model, Sergeant does not make linkages between specific executive functions or include working memory in this model. This model, though a comprehensive explanation of impulsive behaviors, does not provide additional information useful to explanation of working memory deficits. Though his model does not provide insight into working memory dysfunction in children with ADHD, Sergeant and colleagues (2003) note the distinction between top-down and bottom-up processing and that both of these must be considered when examining neuropsychological processing in this population. Though Sergeant and colleagues (2003) advocate for considerations of both top-down and bottom-up mechanisms working memory is, as defined by Baddeley (2003), a top-down process in which higher-order executive processes control lower, slave system processes. Sergeant's model is therefore inconsistent with the theoretical and empirical literature in the area of working memory and will not be applied in the current study.

Comparison of models

Fuggetta (2006) used performance of children with and without ADHD on executive and lower process measures to compare Barkley (1997) and Sergeants' (2000) models. Because Fuggetta (2006) found that children with ADHD had deficits in both processing speed and the executive measures, he concluded that Sergeant's (2000) model was consistent with the lower level processing deficits and Barkley's model was consistent with the executive deficits in that sample. Barkley's (1997) model was, however, the only model of executive dysfunction considered by Fuggetta (2006).

Though similar to Brown (2006) and Barkley's (1997) models, Nigg and Casey's (2005) model appears to be the most empirically and theoretically sound of the models. Nigg and Casey's (2005) discussion of children with ADHD failing to recognize and adapt to environmental stimuli is similar to Barkley's (1997) definition of a central behavior inhibition deficit including failure to inhibit prepotent responses, interrupt ongoing responses, and avoid interference by irrelevant stimuli. Nigg and Casey's (2005) and Brown's (2006) models differ from that of Barkley (1997) in that both Nigg and Casey and Brown suggest a combined effect of multiple executive processes resulting in ADHD executive dysfunction; whereas Barkley (1997) suggests one core executive deficit. Other researchers, such as Swanson and colleagues (1998) support this notion that ADHD executive dysfunction is based on a combination of executive deficits. In addition, both Nigg and Casey (2005) and Brown (2006) indicate that their models can be generalized to all children with ADHD whereas Barkley limits the application of his model of executive dysfunction to children with ADHD Combined-type. Though Nigg and Casey (2005) and Brown (2006) both offer improvements over the Barkley model, Nigg and Casey (2005) provide evidence from neuroimaging studies indicating that the deficits they propose in both inhibition and shifting attention reflect differences in brain size and activation in both the frontostrietal and frontocerebellar loops; whereas Brown (2006) bases his theory solely on behavioral observations.

Nigg and Casey's (2005) model also can be used to explain the variations in working memory performance in children with ADHD. Children with ADHD are able to perform on the same level as their peers when only the slave system of the working memory system is engaged on short-term memory tasks only requiring repetition of

presented information. However, when these children are presented with a task requiring central executive involvement, it is possible that they do not form the linkage between the complex task demands and additional resources that should be provided by the central executive to facilitate completion of the working memory task. Therefore, application of the Nigg and Casey (2005) model expands the relationship between executive processes and working memory in children with ADHD from Barkley's single relationship between inhibition and working memory to a combination of executive control processes including, but not limited to inhibition having a downstream combined effect on working memory performance.

Linkages Between ADHD Symptoms and Executive Functions Performance

Differences have been found between ADHD subtypes and measures of executive functions, though these results have been inconsistent. Heaton and colleagues (2001) found no differences between ADHD combined and ADHD inattentive children's performance on Test of Everyday Attention for Children subtests measuring sustained, selective, and shifting attention. Tsal and colleagues (2005) also did not find differences on performance measures of sustained attention or executive attention. Similarly, using a behavioral rather than performance measure, Gioia and colleagues (2002) found that children with ADHD inattentive and ADHD combined did not differ on the metacognitive scales of the Behavior Rating Inventory of Executive Functions (BRIEF). Willcutt and colleagues (2005) also did not find significant differences in effect size between ADHD subtypes in a meta-analysis of executive functions measures (mean $d = .09$).

In contrast, Gioia and colleagues (2005) found that children with ADHD combined type had significantly higher inhibition scores. Though this does indicate differences in inhibition performance between subtypes, the BRIEF is a behavioral measure rather than a performance measure. These results can only be interpreted to verify behavioral differences used for diagnostic criteria rather than differences in neuropsychological functioning between subtypes.

On performance measures, Tsal and colleagues (2005) found that children in the ADHD-Inattentive subtype made significantly more commission errors than children in the ADHD-Combined subtype. These results are inconsistent with the definitions of the inattentive and combined subtypes in that commission errors are a measure of inhibition. Dysinhibition is a key characteristic of the hyperactive/impulsive and combined types of ADHD rather than the inattentive subtype. The result that children with an inattentive type diagnosis exhibited greater difficulties with inhibition than the other subtypes leads to questions about the diagnoses and the study procedures. This result does, however, indicate that it is necessary to examine the relationships between the various symptom domains of ADHD and performance on executive functions measures.

In addition to examining group differences on executive functions measures across subtypes, it is also useful to examine the relationship between subtypes of ADHD symptoms as a continuous variable and executive functions performance. In a study examining differences of neuropsychological deficits across the subtypes of ADHD, inattentive, hyperactive/impulsive, or combined, Chhabildas and colleagues (2001) used measures of inhibition, vigilance, and processing speed. Inhibition was measured by a continuous performance test and a go/no-go task. Vigilance was measured through

omission errors on the continuous performance test. Using stepwise regression analysis, ADHD Inattentive symptoms were predictive of inhibition, processing speed, and vigilance performance. Symptoms of hyperactive/impulsive or combined ADHD types were not predictive of the dependent measures. On measures of inhibition, inattentive and combined type participants evidenced deficits in reaction times as compared to controls, whereas hyperactive/impulsive participants differed from controls only on commission errors. Subsequent analyses of covariance with inattention as a covariate resulted in all differences in performance between the subtypes and controls being eliminated. Results of this study indicate that inattentive symptoms have the strongest relationship with executive functions performance including inhibition and sustained attention.

Sonuga-Barke and colleagues (2002) also examined the relationship between ADHD symptoms and inhibition performance. They examined preschool children with ADHD symptoms on measures of response inhibition, working memory, and planning. ADHD symptoms correlated significantly with inhibition performance. Working memory was not correlated with ADHD symptoms in this study; however, working memory typically develops after behavioral inhibition in the developmental sequence (P. Anderson, 2002; V. Anderson, 1998). In this young sample, the children's inhibition processes may have been more developed than their working memory processes depending on where each child was in the developmental sequence. This may have contributed to differences in relationships between ADHD symptoms and various areas of executive functioning. The results of both of these studies (Chhabildas, Pennington, & Willcutt, 2001; Sonuga-Barke et al., 2002) strengthen the linkage between symptoms of ADHD and executive functions performance.

Effect of Medication on Executive Functions Performance

In an adolescent sample, Barkley and colleagues (2001) compared the executive functions performance of medicated and non-medicated adolescents with ADHD. Executive performance did not differ between the groups on measures of inattention (CPT Omission errors), working memory (digit span backward), and verbal fluency (F-A-S). There were group differences between medicated and non-medicated adolescents with ADHD on a measure of inhibition (CPT Commission errors) with the medicated teens having significantly worse scores than non-medicated teens. Based on these results Barkley and colleagues (2001) decided to collapse the medicated and non-medicated ADHD groups for analysis. This is consistent with the findings of Heaton and colleagues (2001) that found no differences between medicated and non-medicated children on measures of sustaining, dividing, and shifting attention in children ages 6 to 16. Other studies have found differences between medicated and non-medicated children with ADHD on measures of executive functioning. These differences were found in the areas of spatial working memory (Barnett et al., 2001; Bedard, Martinussen, Ickowicz, & Tannock, 2004; Kempton et al., 1999; Tannock, Ickowicz, & Schachar, 1995), planning, and set shifting (Kempton et al., 1999). Based on these results, the effect of medication on executive functions performance is inconsistent.

Working Memory Performance

Children with ADHD are known to have deficits in multiple areas of cognition including working memory. Working memory deficits have been found in this population as early as preschool age (Mariani & Barkley, 1997). Though inhibition is theoretically linked to working memory performance (Barkley, 1997; Nigg & Casey, 2005) it is

unclear whether inhibition accounts for all of the variance in working memory performance. It has been shown in past research that children with ADHD only evidence working memory deficits if the cognitive demands of the working memory task involve some form of manipulation of information such as on digit reversal tasks as opposed to forward digit tasks (McInnes et al., 2003). Based on current conceptions of working memory (e.g. Baddeley, 2003; Cowan, 1999), it is likely that this occurs when attentional control involvement from the central executive component of working memory is involved in the task rather than relying on the rote rehearsal mechanisms of the slave systems. It has been argued based on this information that the source of working memory deficits in children with ADHD is located in the processes attributed to the central executive (Karatekin, 2004). By examining performance of children with ADHD on various tasks of working memory and the components of Baddeley's model that are utilized for those tasks, hypotheses as to the source of working memory dysfunction in children with ADHD can be made.

Measurement of Working Memory in ADHD Samples

There appear to be two types of working memory measures used in the ADHD literature. The first of these are memory tasks in which the participant is required to remember and manipulate information in some way. These tasks are used primarily in clinical research studies (e.g. Loge, Stanton, & Beatty, 1990; McInnes et al., 2003). The other type of working memory task is using a memory span task combined with another concurrent processing task. These tasks are used primarily in experimental research studies (e.g. Cornoldi and colleagues, 2001; Karatekin, 2004). The tasks used in clinical studies are typically pulled from a cognitive or neuropsychological test battery. This

provides the researcher with standardized scores based on normative data and information about reliability and validity of the measures. Memory tasks in experimental studies are typically designed by the researcher for the specific experiment. Though these tasks provide the researcher with more control over stimuli, there is no standardization data for comparison of participant performance and reliability and validity data are restricted to the study sample limiting external validity. This distinction must be considered when interpreting results of working memory studies in the ADHD population.

Phonological Loop Performance

As previously noted, Barkley (1997) suggests that the phonological loop of Baddeley's (2003) model of working memory is disrupted by dysfunctional behavior inhibition. As suggested by Barkley's model (1997), children with ADHD performed significantly worse than controls on tasks such as combined digit span, Brown Peterson short-term memory number correct, and California Verbal Learning Test trials one, two, four, five, short delay, and long delay (Loge, Stanton, & Beatty, 1990). This study used combined digit span which combines variance from both the phonological loop and the central executive components of the working memory system. It is therefore difficult to distinguish whether this difference in performance between children with ADHD and controls is resulting from the phonological loop, the central executive, or both. Brown Peterson short-term memory and California Verbal learning Task both require children to remember a list of words across multiple repetitions. These results may indicate children with ADHD do not benefit from multiple repetitions of information to the degree that

control children do. There is, however, evidence to indicate that deficient performance on these measures may be a downstream result of central executive impairment.

In a study of children age 8 to 15 with and without ADHD, it was found that there were no differences between children with ADHD and controls on forward digit span, however, on backward digit span children with ADHD had significantly impaired performance (McInnes et al., 2003). Digit span forward is a measure of rehearsal, whereas digit span backward is a measure of manipulation (Reynolds, 1997). This indicates that children with ADHD perform differently from control children when the central executive is involved in a task but not when the phonological loop is the only component required for task completion.

Similarly, in Karatekin (2004), children with ADHD were found to have similar patterns of performance on verbal and spatial simple working memory tasks as compared to control children. The verbal task consisted of remembering a series of letters whereas the spatial task required remembering locations of letters presented but not the letters themselves. It should be noted that responses were measured in terms of recognition of stimuli rather than recall. This may have resulted in better performance for both groups and leads to questions about the generalizability of the results. The accuracy of the children with ADHD's responses did not vary disproportionately to control children's based on increase in memory load or delay. This indicates that the differences in task performance for children with ADHD are a result of the memory task itself not cognitive demand or length of the delay in responding.

Kalff and colleagues (2002) used CBCL scores rather than DSM diagnosis to categorize participants into three groups of 5 and 6 year olds: ADHD, borderline ADHD,

and non-ADHD. Children with ADHD performed significantly lower on number recall and word order K-ABC working memory tasks as compared to children without ADHD. Because they used CBCL scores rather than DSM criteria, results of this study cannot be generalized to children with ADHD as children who did not meet full criteria may have been included in the sample. Similarly, Cornoldi and colleagues (2001) used ADHD symptoms as rated by their teachers as diagnostic criteria. In contrast to Kalff and colleagues (2002), Cornoldi and colleagues (2001) found that children with ADHD did not perform differently than controls on a simple word recall task. These studies illustrate the impact of different diagnostic criteria in ADHD working memory studies in that using arbitrary cut-offs to create groups leads to differences in study outcomes. These two studies use similar measures, number recall and word recall, but produce different results. Results of the Cornoldi and colleagues (2001) study is similar to that of other studies indicating that children with ADHD do not evidence deficits in phonological loop performance. The results of the Kalff and colleagues (2002) study indicates that these results may not be consistent depending on diagnostic criteria used.

Martinussen and colleagues (2005) conducted a meta-analysis of studies including working memory measures in children with ADHD and controls. They categorized working memory measures into verbal storage, verbal central executive, spatial storage, and spatial central executive measures. Results indicated a moderate mean effect size for both the verbal storage ($d = .47$) and verbal central executive ($d = .56$) working memory measure categories; however, the results may be confounded by the inclusion of total digit span (i.e. combined results of digits forward and backward) score in the verbal storage category. The authors indicate that removal of total digit span from the analysis

did not change the results of the verbal storage category; however, the potential impact of inclusion of digits forward results into the verbal central executive category was not addressed. These results, though confounded by the digit span measure, indicate that there may be group differences between children with ADHD and controls on verbal storage, or phonological loop, measures, though this difference may be smaller than that of the verbal central executive measures.

Overall, results of studies using tasks that tap the phonological loop of the Baddeley (2003) model appear to indicate that children with ADHD perform at the same level as control children when working memory tasks require only phonological loop processes for completion. There is, however, some discrepancy among the studies with Kalfs and colleagues (2002) and Loge, Stanton, and Beatty (1990), finding deficient performance in ADHD children and Karatekin (2004) and McInnes and colleagues (2003) finding equivalent performance between children with ADHD and controls on phonological loop tasks. Further investigation is necessary to clarify if impairment in the phonological loop component contributes to working memory deficits in children with ADHD, or if all working memory impairment is the result of central executive dysfunction.

Visuospatial Sketchpad Performance

Barkley defines nonverbal working memory in children with ADHD as covert self-direction of behavior and sensory experiences (Barkley, 1997). This includes seeing and hearing within the self. Behaviors listed under the umbrella of nonverbal working memory include holding events in mind, manipulating events in mind, imitation of complex behavior sequences, retrospective and prospective memory function, and sense

of time. These functions are thought to be localized in the dorsolateral prefrontal cortex and are related to the visuospatial sketchpad in Baddeley's model of working memory (Barkley, 1997). Similar to the phonological loop, Barkley (1997) states that nonverbal working memory, or the visuospatial sketchpad is disrupted by behavioral disinhibition. As previously stated, the functioning of the visuospatial sketchpad is less well researched than the phonological loop because of difficulty with manipulation of nonverbal information for experimental purposes (Baddeley, 2003). This difficulty is also reflected in the ADHD working memory literature as there is less evidence to support or refute deficits in visuospatial sketchpad functioning. For example, as previously stated, Karatekin (2004) found that children with ADHD had similar performance to control children on a spatial working memory measure requiring them to remember locations of letters. This supports the idea that deficits in working memory performance in children with ADHD are not the results of slave system dysfunction.

Goldberg and colleagues (2005) used a spatial working memory measure in which the participants had to find tokens in a number of boxes on the computer screen using a touch screen. Once a token was found in a box, it would not appear there again. The test consisted of 4, 6, and 8 box conditions. If a box that previously had a token was selected again or if a box was repeatedly chosen after being found empty, an error was counted. Children were therefore required to retain which boxes had had tokens on previous trials and which boxes they had already opened on the current trial. Children with ADHD were found to have significantly more errors on the working memory measure as compared to controls. They made more between trial errors, i.e. opening a box that had already been found to contain a token, than control children when the task difficulty increased from 4

and 6 to 8 boxes. There was not a significant difference on within task errors. This indicates that the children with ADHD were able to retain which boxes had been opened on each trial; however, when the number of boxes increased to 8 they were unable to maintain which boxes had previously contained tokens. This suggests that at the 8 box level, the combined tasks of remembering which boxes had been opened on each trial and which boxes had previously contained tokens exceeded their working memory capacity (Goldberg et al., 2005). Based on Baddeley's model, the coordination of remembering the information for the current trial and the information from the previous trials may have required central executive involvement. The results that children with ADHD did not differ from controls until the demands reached the 8 box level appear to also support that the slave system, visuospatial sketchpad, resulted in equivalent performance but when the capacity of the slave system was exceeded and the central executive was required to assist with task performance there was a difference between children with ADHD and controls.

Kerns and colleagues (2001) also found that memory performance did not differ between children with ADHD and controls on a working memory game that required the children to remember locations of stimuli and on a task requiring participants to point to different stimuli on each page. This is consistent with other findings that children with ADHD do not differ from controls on measures of visuospatial sketchpad functioning that do not tap the central executive.

Results of these studies, that children with ADHD and controls have equivalent performance on a spatial working memory tasks requiring them to remember locations of stimuli (Karatekin, 2004) and on less complex levels of a box opening task (Goldberg et

al., 2005), appear to indicate intact functioning of the visuospatial sketchpad. Any deficits in performance observed in these studies appear to result from central executive impairment rather than visuospatial sketchpad functioning.

Central Executive Performance

As results of studies examining slave system performance appear to indicate central executive involvement in working memory deficits of children with ADHD, performance of children with ADHD on tasks tapping the central executive, in addition to and apart from the slave systems, must be examined. Children with ADHD are found to consistently have more difficulty than controls on tasks in which they are required to recall and manipulate the information, such as the span tasks first used by Daneman and Carpenter (1980). Cornoldi and colleagues (2001) compared children with ADHD and control children, age 8 to 12, on a listening span task that required them to listen to a string of words and tap the table when they heard an animal word. After a set of five word strings had been read, the child was asked to repeat the last word of each string. Children with ADHD were found to recall fewer words overall and have more intrusions, or words that were not part of the original string.

In imaging studies of central executive performance, differences in brain area activation have been found. Using a 2-back working memory task, pressing the target button when a letter is the same as a letter displayed 2 letters before it, it was found that activation was less diffuse in adults with ADHD (Valera et al., 2005). This indicates that fewer cortical areas are used on working memory tasks in individuals with ADHD. Specifically, Valera and colleagues (2005) found that there was less cortical activation in the cerebellum, occipital cortex, and right prefrontal cortex. In this same study, it was

reported that there were no areas of the brain that had greater activation in participants with ADHD than controls (Valera et al., 2005). Though the ADHD and control adults were found to have differences in activation during the working memory measure, their performance on this task did not differ. The researchers hypothesize that this is due to reorganization of processes that may have taken place by adulthood to allow for compensation of ADHD related deficits (Valera et al., 2005). Further research is needed to investigate whether these differences in activation occur in children with ADHD and how this relates to differences in children's performance on working memory tasks.

To examine central executive functioning, Karatekin (2004) utilized a dual-task methodology requiring children with ADHD and controls to complete a forward digit span task while completing a reaction time measure. These results were compared to baseline reaction time results to measure the cost of adding the digit span task and tapping the central executive through dual task coordination. Results indicate that children with ADHD had significantly slower reaction times in the dual task condition as compared to controls. Reaction times of the ADHD group were also more variable than those of controls (Karatekin, 2004). A limitation in this study is that variability in reaction times could be attributed to the ADHD participants having difficulty fixating on the screen for the reaction time task. It is questionable as to why the reaction time measure was used as the dependent variable rather than the memory measure in a study evaluating memory. It appears that central executive functioning in the context of working memory would be better understood by looking at the cost of adding coordination of two tasks to a baseline memory measure rather than a baseline reaction time measure. Despite this limitation, the study does appear to indicate that children with

ADHD have greater difficulties than control children on memory tasks requiring central executive involvement.

In another dual task paradigm, Fuggetta (2006) used computer presentation of form and color stimuli. In the single task condition, participants responded on a keyboard indicating if presented stimulus was a “2” or a “5”. Response times were recorded. In the dual-task paradigm, participants again discriminated between forms; however, they also had to name the background color of the stimulus screen. When comparing response times of boys (ages 8 to 11) with and without ADHD, it was found that boys with ADHD had longer reaction times overall. In addition, boys with ADHD also exhibited a greater increase in their response times between the single and dual task conditions. Fuggetta (2006) suggests that these results show that children with ADHD have overall slower processing, but that they also have executive deficits that interfere with coordination of multiple tasks. As multiple processing demands are a key feature of working memory tasks tapping the central executive (Baddeley, 2003), this study (Fuggetta, 2006) provides further evidence of central executive deficits in children with ADHD.

Willcutt and colleagues (2005) found significant differences in effect size between children with ADHD and controls in a meta-analysis of verbal and spatial working memory measures requiring central executive functioning. The verbal working memory tasks in the meta-analysis were digits backward and a sentence span task in which children were required to remember the last word of a series of sentences. The spatial working memory tasks used in the meta-analysis were self-ordered pointing and the previously mentioned box opening test of the CANTAB. Similarly, results of meta-analysis by Martinussen and colleagues (2005) indicate that there is a greater effect size

between children with ADHD and controls on working memory measures requiring manipulation, the key difference between central executive and slave system tasks, relative to differences in performance on tasks requiring only storage.

Fractionated Central Executive Task Performance

Because there is evidence that deficits in working memory performance in the ADHD population are the result of central executive impairment (Barkley, 1997; Fuggetta, 2006; Goldberg et al., 2005; Karatekin, 2004; Martinussen et al., 2005; Valera et al., 2005; Wilcutt et al., 2005), it is necessary to examine the fractionated processes of the central executive to determine if each process contributes to deficits in working memory performance in children with ADHD. As previously determined, the fractionated components of the central executive included in the current model are: (a) sustained attention, (b) selective attention/inhibition, (c) shifting attention, and (d) control of retrieval from long-term memory. Impairment in each of these processes may contribute to deficits in working memory in the ADHD population.

Sustained Attention

Sustained attention is defined as the capacity to maintain attention over time (Lezak et al., 2004; Mirsky et al., 1991). Barkley and colleagues (2001) found that sustained attention loaded on a separate factor from inhibition and working memory in a sample of adolescents with ADHD. In this same study, children with ADHD were found to have greater inattention scores than control children indicating that they committed more omission errors and had greater variability in their reaction times on a continuous performance test measure. Children with ADHD were found to have significantly more omission errors on a go/no go (Kerns, McInerney, & Wilde, 2001) and sustained attention

reaction time tasks (Shallice et al., 2002) than normal control children. Muir-Broddus and colleagues (2002) found children with ADHD to perform three standard deviations below the test norm group on visual continuous performance task omission errors.

Children with ADHD had significantly longer reaction times than controls on a sustained attention reaction time measure in which they were required to name all numerals that appeared on the screen except for a pre-identified target number (Shallice et al., 2002). They also had more omission and commission errors. In the same study, children with ADHD performed as well as control children on number of correct responses on a vigilance measure. The procedure for this measure was similar to the reaction time measure except that the participants were only asked to name the target numeral. This measure was therefore thought to tap sustained attention more than the first reaction time measure in which children named all numbers except the target. On this task children had to maintain attention to the task across several numerals that did not require a response. These results appear to indicate that the children with ADHD did not have difficulty sustaining their attention if a consistent response was required, but did have difficulty sustaining attention and inhibiting responses when inconsistent responses were required.

Heaton and colleagues (2001) found that children with ADHD performed significantly worse than clinical controls on single task sustained attention measures from the Test of Everyday Attention for Children (Manly, Robertson, Anderson, & Nimmo-Smith, 1999). Manly and colleagues (2001) also found boys with ADHD to have poorer performance than control boys on measures of sustained attention from the TEA-Ch after controlling for age and block design performance. Heaton and colleagues (2001) did not

find significant differences between children with ADHD and clinical controls on dual-tasks measures of sustained attention requiring the child to divide and sustain attention rather than simply sustaining attention as in single task measures. As these measures require use of a several attentional processes, the lack of significant differences between these groups does not suggest that children with ADHD do not differ from clinical controls on measures of sustained attention. Rather, it suggests that further investigation is required to determine the relationships among attentional processes and how their interactions affect performance.

In addition to the consistent group differences found between children with ADHD and control children on measures of sustained attention, Tsal and colleagues (2005) conducted effect size comparisons across measures of selective, sustained, executive, and orienting attention and found that sustained attention was the most pronounced deficit in the ADHD group relative to normal control children. In summary, children with ADHD exhibit consistent deficits in sustained attention relative to control children and this deficit is also shown to have the largest effect size of all types of attention.

Selective Attention/Inhibition Processes

Inhibition or selective attention is defined as the capacity to focus on important stimuli while suppressing irrelevant stimuli (Baddeley, 1996; Barkley, 1997; Lezak et al., 2004; Mirsky et al., 1991). In a longitudinal study of children with ADHD from age 5 to 8, it was found that inhibition performance in preschool was predictive of executive functions performance and ADHD symptoms at school age (Berlin, Bohlin, & Rydell, 2003). Because inhibition is the first of these executive functions to develop (P.

Anderson, 2002; V. Anderson, 1998), deficits in the central executive can be observed as early as preschool years by measuring inhibition performance.

As previously discussed, ADHD symptoms have been linked empirically to inhibition. For the purposes of this study, it is also necessary to connect ADHD working memory performance to inhibition. Cornoldi and colleagues (2001) required children with ADHD and controls between the ages of 8 and 12 to recall the last word of a word list and to tap the table when the word was an animal. They then performed the same task and recalled all of the words on the list. Their results indicate that children with ADHD recalled a lower percentage of last words as compared to controls. They also committed more intrusion errors, recalling animal words not on the list, during the recall task in which they were required to remember all words from the list. This indicates that inhibition performance, as measured by intrusions, is impaired during working memory tasks in addition to during pure inhibition measures such as go/no-go tasks. The performance of children with ADHD remained significantly different from that of controls after controlling for motor inhibition. This indicates that the difference in performance can be attributed to cognitive inhibition rather than to motor/behavioral inhibition. It should be noted, however, that the diagnostic criteria used for this study was teacher reported symptoms. Barkley (2003) reports that using teacher reported symptoms alone results in much higher prevalence rates as compared to multiple raters; therefore, participants may have been included in the study sample that do not meet full DSM criteria which states that symptoms must be present in multiple settings (American Psychiatric Association, 2000).

Stevens and colleagues (2002) measured behavioral inhibition with a stop-signal task with and without reinforcement and working memory with a digits and color memory test. To test the relationship of inhibition and working memory presented in Barkley's model (1997a), Stevens and colleagues (2002) examined the relationship between working memory performance and behavioral inhibition. A negative correlation was found between inhibition and working memory scores in both ADHD and control groups indicating that greater inhibition deficits coincide with decreased working memory performance.

Children with ADHD performed significantly worse than controls on vigilance task commission errors and number correct and commission errors on a distractibility task (Loge, Stanton, & Beatty, 1990). Similarly, Muir-Broaddus and colleagues (2001) found children with ADHD to perform one standard deviation below the test norm group on a visual continuous performance test commission errors.

In contrast, using a Stroop task, Goldberg and colleagues (2005) found that ADHD, high-functioning autistic, and control children did not differ in inhibition performance. They determined from their results and past research that the Stroop task should not be used as an indication of response inhibition in the ADHD population due to the high rate of comorbidity with reading disability and rapid automatic naming deficits that together can affect all three conditions of the Stroop task. Though Goldberg and colleagues (2005) were able to explain why their results differed from the majority of the literature, this study indicates some inconsistency in the results of inhibition task performance in the ADHD population.

Results of meta-analysis indicate significant differences in effect size on measures of response inhibition in children with ADHD and controls (Willcutt et al., 2005). There was a moderate effect size for these group differences. Children with ADHD also had more commission errors than controls on two number-naming tasks combining sustained attention and inhibition (Shallice et al., 2002). These results may indicate that children with ADHD had more difficulty inhibiting than controls. An alternative explanation could be that children with ADHD demonstrate commission errors when they are having difficulty sustaining attention in an effort to refocus (Shallice et al., 2002). On a sentence completion measure in which children with ADHD and normal controls were required to complete a set of sentences with an inappropriate word, children with ADHD made more errors in terms of saying a word that completed the sentence and saying a word related to one that completed the sentence (Shallice et al., 2002). In addition, on this task only 9.5% of children with ADHD reportedly used a strategy for the task as compared to 47% of the control children (Shallice et al., 2002). Shallice and colleagues (2002) suggest that the lack of strategy use by children with ADHD resulted in an inhibitory control problem when trying to produce an unrelated response.

Manly and colleagues (2001) found that boys with ADHD had significantly poorer scores on measures of selective attention in the TEA-Ch battery as compared to controls. These differences were, however, eliminated after controlling for block design performance. The authors indicate that this result may be due to the fact that block design and the selective attention measures are all timed and therefore share that variance.

Berlin and colleagues (2004) found boys with ADHD to commit significantly more commission errors on a go/no/go task and more errors on a Stroop-like task as

compared to age and ethnicity matched controls. As previously noted, they also found that inhibition contributed unique predictive variance to logistic regression equations predicting ADHD or control group membership.

In contrast, Barkley and colleagues (2001) found no group differences between adolescents with and without ADHD on factor analytically derived inhibition. This factor was composed of continuous performance test commission errors and hit rate. Similarly, Kerns and colleagues (2001) found children with ADHD and controls to have equivalent performance in terms of commission errors on a go/no go task and on a CPT. These groups also did not differ on the Stroop interference condition.

Shifting Attention

Shifting attention is defined as the ability to change focus in a flexible manner (Lezak et al, 2004; Mirsky et al., 1991). Baddeley defines this component of the central executive as the “capacity to shift attention from one task to another” (Baddeley, 2002a, pg. 252). On a set-shifting task similar to the Wisconsin Card Sorting Test (Goldberg et al., 2005) no differences were found between children with ADHD, high-functioning autism, and controls. The researchers attribute this to a ceiling effect; however, other studies confirmed these findings. Children with ADHD also did not differ from controls on the Wisconsin Card Sorting Test (Loge, Stanton, & Beatty, 1990; Scheres et al., 2004) though these authors concede that these results are not consistent with past research. Children with ADHD committed more perseverative errors on the Junior Brixton Spatial Rule Attainment Test (Shallice et al., 2002) indicating difficulty shifting attention relative to control attention. This test is also similar to the Wisconsin Card Sorting Test in that the participant is required to shift rules used for card placement after nine correct trials.

In contrast, Heaton and colleagues (2001) found significant differences in performance on attentional control subtests requiring children to shift their attention, Creature Counting and Opposite Words, of the Test of Everyday Attention for Children with children with ADHD performing worse than clinical controls. Manly and colleagues (2001) also found boys with ADHD to have significantly poorer performance than controls on measures requiring attention switching in the TEA-Ch battery. Results of meta-analysis also indicates a significant effect size between children with ADHD and controls on measures of set-shifting (Willcutt et al., 2005); however, the effect size of the Wisconsin Card Sorting Test ($d = .46$), a well-known measure of set-shifting, is the smallest of the 13 executive functions measures included in the meta-analysis.

Using an experimental paradigm with computer-presented stimulus, Fuggetta (2006) found that boys with ADHD did not commit more errors on an attention shifting task, but they did have longer reaction times than controls when completing an attention shift indicating that the attention shift required more processing and was therefore more difficult for children with ADHD. These results remained significant after controlling for baseline reaction times.

Based on the inconsistency in past research findings, further investigation is needed to determine whether children with ADHD exhibit deficits in shifting attention. Investigation is also needed to determine if performance on these tasks is related to working memory performance.

Control of Retrieval of Information from Long-term Memory

Baddeley defines “the capacity for the temporary activation of long-term memory” (Baddeley, 1996, pg. 22) as the responsibility of the episodic buffer (Baddeley,

2002a, 2002b). In the episodic buffer component of Baddeley's (2003) model, information is accessed from episodic long-term memory and combined with new information to form new representations. This component is then controlled by the central executive, indicating that the central executive is in control of retrieval of information from long-term memory. The process control of retrieval from long-term memory has recently been localized in the left-inferior pre-frontal cortex with involvement of the temporal, frontal, and parietal regions (Buckner, 1996; Noppeney, Phillips, & Price, 2004; Wagner, Pare-Blgouv, Clark, & Poldrack, 2001). This component of the central executive appears similar to Barkley's (1997) concept of reconstitution. Barkley (1997) relates reconstitution to verbal and behavioral fluency. Other researchers have indicated that impaired verbal fluency reflects central executive dysfunction (Azuma, 2004).

In a factor analysis of executive functions performance in adolescents with ADHD, Barkley and colleagues (2001) found that fluency measures and working memory measures loaded on the same factor. On the combined working memory/fluency factor in this study, adolescents with and without ADHD did not differ.

Chertkow and Bub (1990) determined that deficient performance on verbal fluency measures in the Alzheimer's population were related to two deficits: (a) deterioration of the semantic store or (b) deterioration of retrieval processes. The number of words retrieved in the verbal fluency task appears to be dependent upon the capacity of the semantic store; whereas, errors on the task appear to specifically reflect difficulties with the retrieval process (Chertkow & Bub, 1990).

Consistent with the factor loadings of Barkley and colleagues (2001), Azuma (2004) also provides empirical support for a relationship between the executive component of working memory and verbal fluency. Azuma (2004) examined the effect of increasing levels of working memory load on verbal fluency performance. Results of analysis of variance indicated that higher working memory loads did not impact the number of words produced on semantic fluency tasks; however, higher memory loads did result in a significantly greater number of errors. These results were consistent across both letter and semantic forms of verbal fluency (Azuma, 2004). This indicates that errors in verbal fluency are more closely related processes to memory performance than number of words produced in verbal fluency tasks. This suggests that errors on verbal fluency are more representative of control of retrieval than number of words.

Supporting a deficit in this area of the central executive, children with ADHD had significantly more rule violations on letter fluency and design fluency as compared to controls (Loge, Stanton, & Beatty, 1990). Consistent with these results, in a study by Scheres and colleagues (2004), boys with ADHD had significantly lower scores on the Controlled Oral Word Association Test, a verbal fluency measure. These differences were not significant after controlling for age and IQ; however, as verbal fluency is a cognitive ability included in models of intelligence (e.g. Cattell-Horn-Carroll; Carroll, 1993; McGrew & Evans, 2004), it is likely that controlling for IQ removed a large portion of the verbal fluency variance.

Deficits in this area of the central executive are not consistent. In a study by Shallice and colleagues (2002) children with ADHD did not perform differently than controls on a letter fluency measure. In addition, Tucha and colleagues (2005) found that

adults with ADHD produced fewer words overall on both phonemic and semantic fluency; however, they did not make more errors than adult controls.

Patterns of Performance and Summary

Based on the components of Baddeley's (2003) model of working memory, it appears that children with ADHD have deficits primarily in the central executive component of the model. In children with ADHD, phonological loop and visuospatial sketchpad performance appear to be equivalent to control peers (Cornoldi et al., 2001; Goldberg et al., 2005; Karatekin, 2004; Kerns, McInerney, & Wilde, 2001; McInnes et al., 2003). In working memory tasks involving the central executive, there is evidence of impaired performance (Cornoldi et al., 2001; Fuggetta, 2006; Goldberg et al., 2005; Karatekin, 2004; Martinussen et al., 2005; Valera et al., 2005; Willcutt et al., 2005). Consistent deficits in sustained attention are evident in the literature (Heaton et al., 2001; Kerns, McInerney, & Wilde, 2001; Manly et al., 2001; Muir-Broddus et al., 2002; Shallice et al., 2002; Tsal, Shalev, & Mevorach, 2005). The relationship between sustained attention and working memory is also established theoretically and empirically (Barkley, 1997; Berlin, Bohlin, & Rydell, 2003). Further investigation is warranted to determine if sustained attention, as a component of the central executive, contributes to the relationship between ADHD symptoms and working memory performance.

When examining the fractionated processes of the central executive it is evident that selective attention/ inhibition performance is the most researched area of the central executive. Though there is some inconsistency (Barkley et al., 2001; Goldberg et al., 2005; Kerns, McInerney, & Wilde, 2001), a deficit in the inhibition process and theoretical and empirical linkages between this process and working memory

performance is firmly established in the ADHD literature (Berlin, Bohlin, & Rydell, 2003; Berlin et al., 2004; Chhabildas, Pennington, & Willcutt, 2001; Cornaldi et al., 2001; Loge, Stanton, & Beatty, 1990; Manly et al., 2001; Muir- Broddus et al., 2001; Shallice et al., 2002; Stevens et al., 2002; Willcutt et al., 2005).

ADHD performance in the area of shifting attention is inconsistent in the literature. Some studies indicate performance equivalent to control children (Goldberg et al., 2005; Loge, Stanton, & Beatty, 1990; Scheres et al., 2004); whereas, others indicate deficits in performance for children with ADHD relative to control children (Fuggetta, 2006; Heaton et al., 2001; Manly et al., 2001; Shallice et al., 2004; Willcutt et al., 2005). The relationship between shifting attention and working memory is also established theoretically and empirically (Baddeley, 2002a); however, this relationship has not been explored in relation to ADHD symptoms.

The construct control of retrieval is empirically and theoretically linked to working memory (Azuma, 2004; Barkley, 1997a; Buckner, 1996; Chertkow & Bub, 1990; Noppney, Phillips, & Price, 2004; Wagner et al., 2001); however, this relationship needs to be further demonstrated in an ADHD population. For the construct control of retrieval, there are mixed results indicating inconsistent performance in the ADHD population on fluency measures. Children with ADHD were found to make more mistakes than controls on fluency measures (Loge, Stanton, & Beatty, 1990; Scheres et al., 2004); however, most studies have indicated that children with ADHD do not differ from controls in terms of frequency of errors on verbal fluency tasks (Barkley et al., 2001; Shallice et al., 2002; Tucha et al., 2005). The control of retrieval construct is,

however, noticeably less well-researched than the other central executive constructs indicating that further study is needed.

Based on this review it is evident that further research is needed to clarify the relationships between ADHD symptoms and working memory performance and the relationships between various central executive processes and overall working memory performance. Further research is also needed to determine which processes of the working memory system contribute to working memory deficits in children with ADHD. Specifically, because performance on slave system tasks appears to indicate intact functioning within the ADHD population, it is necessary to investigate which processes of the central executive contribute to working memory dysfunction. Procedures for addressing these limitations in the current literature will be delineated in the next chapter.

CHAPTER III

METHODS

Dataset Description

Data was obtained from a pre-existing database at Allegheny General Hospital that includes children assessed by psychologists. Participants in the database range in age from age 5 to 16. The database given to the researcher included participants' identification numbers, gender, race, handedness, and scores on chosen assessment instruments. The database currently contains assessment results for approximately 130 children.

Participant information is collected through a standard retrospective chart review process. The information for each patient is transferred from their chart to a summary sheet. The database is then created using demographic, assessment, and diagnostic information from the summary sheets. The database is continually updated by research assistants using this chart review process as more children are assessed. Participants will be outpatients in the department of neuropsychology at Allegheny General Hospital. Participants were referred for evaluation for clinical rather than research purposes. The database and all associated procedures for data entry have been approved by the Institutional Review Board of Allegheny General Hospital. Parents completed informed consent procedures for assessment prior to the initiation of evaluation. Identifying information is removed from all data prior to entry into the database.

Participants

Participants are children ages 8 to 16 taken from a database of children assessed in an outpatient neuropsychology clinic. The sample is a clinical sample of children that

successively came to the clinic for evaluation and were given all of the measures included in the study as part of their neuropsychological assessment. Exclusionary criteria will include diagnoses of mental retardation and/or autism spectrum disorders.

Power Analysis

As path analysis, a structural equation modeling technique with constructs represented by a single variable, is the most parsimonious statistical approach to testing multiple mediators, a power analysis was completed to determine adequate sample size. According to Kline (2005), sample size for path analysis is determined by two factors: number of parameters and model complexity. Kline (2005) suggests a ratio of 10 to 20 participants to each path. For the current model, this would indicate a minimum sample size of 110 to 220 participants. To estimate minimum sample size based on model complexity, degrees of freedom for the model are calculated by subtracting the number of parameters from the number of observations. The degrees of freedom for the model are then compared to tables (MacCallum et al., 1996) indicating requisite sample sizes and associated power. For the current model, there are 17 degrees of freedom. For power of .80, a sample of approximately 500 participants is needed. If the sample size is 200, the power will be .41. Adequate sample size is unavailable, thus another method of testing mediation effects must be used.

The current study utilized a series of regression equations to establish the independent variables and to test the mediation variables. Adequate sample size was determined a priori based on the most complex regression equation consisting of five predictor variables. According to Stevens (2002), a priori power analysis for multiple regression is based on the population multiple correlation. None of the specific

regression equations to be included in the current analyses have been reported in the literature. The closest relationship is that of executive functions and symptoms of ADHD. Executive functions were found to explain 18% of the variance in hyperactive/impulsive symptoms of ADHD and 43% of the variance in inattention symptoms (Berlin, Bohlin, & Rydell, 2003). A priori power was calculated using the smaller coefficient in order to achieve a conservative estimate of needed sample size. Based on a population multiple correlation of .18, power of .80 (Cohen, 1988), and an alpha level of .05, the necessary sample size for the current study is 65 for 5 predictors (Faul, Erdfelder, & Lang, in press). As the database to be used currently has 130 cases, power was expected to be sufficient for the current study.

Measures

ADHD Symptoms

ADHD symptoms were measured with the Attention Deficit Disorder Evaluation Scale Home Version (ADDES; McCarney, 1989). It consists of 46 items divided into three symptom domains: (a) inattentive symptoms, (b) hyperactive symptoms, and (c) impulsive symptoms. These symptom domains are designed to correspond with diagnostic symptom domains of ADHD. The total raw score for each domain is converted to a standard score for that symptom domain. Domain standard scores are also added and converted to an overall percentile for ADHD behaviors. A parent or caregiver completes the rating scale and indicates the frequency of each behavior on a 0 to 4 scale with 0 indicating the child does not engage in the behavior and 4 indicating the child engages in the behavior several times each hour. The measure is designed for children ages 4.5 to 20. It was standardized on 4,876 children with and without ADHD in grades K-12. The

standardization sample matched national percentages of race, sex, area, and parent occupation (McCarney, 1989).

Internal consistency for the ADDES is reported to be .97 (McCarney, 1989). Inter-rater reliability for the three subscales ranges from .81 to .90. Concurrent construct validity is established in that the ADDES correlates significantly with the Conners Scales. The ADDES also exhibits discriminant construct validity in that there are significant mean differences between children with and without ADHD on all three domain standard scores and for the total percentile (McCarney, 1989).

Short-term Memory

Short-term memory was assessed using the Digits Forward subtest of the Wechsler Intelligence Scale for Children – Fourth Edition (WISC-IV; Wechsler, 2003). The WISC-IV battery is designed to measure cognitive functioning in children ages 6 to 16. The WISC-IV was standardized on 2,200 children with total for ethnicity, geographic area and parent education matching 2000 census data.

The Digit Span subtest is comprised of two tasks: (a) Digits Forward and (b) Digits Backward. Digits Forward requires the child to repeat a sequence of numbers in the same order as they are read by the examiner and is a measure of rote memory; whereas, Digits Backward, requiring the child to reverse a sequence of numbers read by the examiner, is a measure of working memory (Reynolds, 1997; Wechsler, 2003). Leffard and colleagues (2006) and Lezak and colleagues (2004) report that forward digit span is a measure of short-term storage capacity. Digits Forward rather than total digit span will therefore be used as the indication of short-term memory. For Digits Forward, there are 8 items with 2 trials each for a total of 16 trials.

Split-half reliability for Digits Forward is reported as .83 in typical children. Internal consistency for combined Digit Span with typical children and with the ADHD population is .87 indicating that this measure is also appropriate for use with the ADHD population. Construct validity for total digit span is established through correlations with the Children's Memory Scales verbal immediate memory (.31), general memory (.30), and attention/concentration (.72) scales. Total Digit Span also loads on the working memory index factor of the WISC-IV factor structure and correlates .86 with the WISC-IV Working Memory Index (Wechsler, 2003) as a further indication of adequate construct validity.

Working Memory

The working memory measure for this study was the Letter-Number Sequencing subtest of the WISC-IV (Wechsler, 2003). Letter-Number Sequencing (LNS) is a core subtest of the WISC-IV Working Memory Index. Administration of the test involves the examiner reading a series of numbers and letters to the child. The child is then asked to repeat back the numbers in sequential order followed by the letters in alphabetical order. The test consists of 10 items with 3 trials each for a total of 30 trials. The test is reported to measure working memory, mental manipulation, and attention among other processes (Wechsler, 2003). Internal consistency for this subtest in the standardization sample was .90 for typical children and .94 in the ADHD population indicating low levels of measurement error and appropriateness of the measure for assessment of children with symptoms of ADHD. LNS is also found to be a valid measure of working memory. In a factor analytic studies of the WISC-IV, LNS is found to load on the factor labeled working memory (Wechsler, 2003) consisting of LNS and combined Digit Span. It also

correlates with memory subtests of the Children's Memory Scales such as General Memory ($r_{xy} = .50$), Attention/Concentration ($r_{xy} = .46$), and Learning ($r_{xy} = .47$; Wechsler, 2003) indicating adequate construct validity. Crowe (2000) also established construct validity of LNS through use of hierarchical regression. His results confirm that the variance in LNS performance is primarily working memory variance. Lezak and colleagues (2004) also report that Letter-Number Sequencing is a measure of working memory and that it is more sensitive to attentional deficits, as compared to digits backward, because of the higher task demands. All of these results indicate that LNS is an appropriate choice to represent the construct working memory in the current study.

Sustained Attention and Selective Attention/Inhibition

Conners' Continuous Performance Test II (CPT; Conners, 2002) was used to assess both sustained attention and selective attention/inhibition. To complete the CPT, children sit at a computer and a series of letters are presented on the screen. The children are instructed to press the spacebar on the keyboard when they see any letter except "X". They are told to not respond when the letter "X" appears. Reaction times are recorded for each letter presented. The test lasts approximately 15 minutes. Omission errors, defined as the child not pressing the space bar in response to a letter other than "X", will be the measure of sustained attention. Commission errors, defined as the child pressing the spacebar in response to the letter "X", will be the measure of selective attention/inhibition.

Omission Errors

Reliability is firmly established for the CPT II. Split-half reliability for Omission errors is .94 in the standardization sample (Conners, 2002). To establish validity of the

measure, the test authors report results of studies comparing performance of children and adults with ADHD, neurological impairment, and normal controls. Results of these studies indicate that CPT Omission errors discriminate between individuals with ADHD and controls and between neurologically impaired individuals and controls (Conners, 2002; Riccio et al., 2002). This is evidence of discriminant construct validity. Lezak and colleagues (2004) indicate that the CPT II is a valid measure of sustained attention due to the length of the test and measurement of omission errors.

Commission Errors

Split-half reliability for CPT II Commission errors is .83 in the standardization sample (Conners, 2002). Results of analyses comparing commission errors of children with ADHD and controls indicated that commission errors do not discriminate children with ADHD from control children. Commission errors were found to discriminate between a group of adults with ADHD and neurological impairments and a group of control adults. These results provide evidence of discriminant construct validity, though it may be inconsistent (Conners, 2002). Lezak and colleagues (2004) indicate that commission errors are a valid measure of inhibition because the individual is required to inhibit pressing the space bar for the letter “X”. The test manual indicates that commission errors should be interpreted as errors in inhibition (Conners, 2002). Commission errors have also been used throughout the literature as an indication of impulsivity or disinhibition (e.g. Barkley et al., 2001) indicating established construct validity for commission errors as a measure of inhibition.

Shifting Attention

Shifting attention was measured with the Delis-Kaplan Executive Function System (D-KEFS; Delis, Kaplan, & Kranmer, 2001) Trail-Making Test. The D-KEFS is a battery of neuropsychological tests designed to assess executive functioning in individuals ages 8 to 89. The battery was standardized on a sample of 1,750 stratified for age, sex, race/ethnicity, years of education, and geographic area based on 2000 census data (Delis, Kaplan, & Kranmer, 2001). The D-KEFS Trail-Making Test requires the participant to sequence visually presented numbers and letters. The test includes 4 baseline conditions and 1 higher-level condition. All conditions are timed and the participant is encouraged to focus on both speed and accuracy. The baseline conditions are Visual Scanning, Number Sequencing, Letter Sequencing, and Motor Speed. For Visual Scanning, the participant searches for and crosses out all occurrences of the number 3 on the page. For Number Sequencing and Letter Sequencing, the participant connects the numbers and letters in numerical or alphabetical order respectively. For the Motor Speed condition, the participant traces a dotted-line around the page in a fashion similar to that required to complete the sequencing tasks. The higher-level condition is Number-Letter Switching. In this condition, the participant alternates connecting numbers in numerical order and letters in alphabetical order. Standard scores for the Trail-Making Test are based on task completion time. The standard score to be utilized in the current study is Number-Letter Sequencing vs. Number Sequencing. This score is representative of the contrast in completion time between the shifting condition and the sequencing condition and is therefore an indication of isolated shifting variance of the Trail-Making Test. By using the contrast score rather than the Number-Letter Switching condition, processing and

motor speed are controlled for and differences in performance across participants are reflective of differences in shifting rather than differences in processing speed, motor speed, and number sequencing.

Reliability for the D-KEFS Trail-Making Test is consistent with that of other executive functions measures. Internal consistency ranges from .59 to .78 across the age groups included in the current study (Delis, Kaplan, & Kramer, 2001). As evidence of validity, the Trail-Making Test has a long history of use in the field of neuropsychology. It was originally designed for the Army Individual Test Battery in 1944 and has been included in batteries designed to measure neuropsychological processes since that time including the Halstead-Reitan Battery. The Trail-Making Test was originally a two step procedure with sequencing as the first task and shifting as the second task. Across the years of its use, it has been expanded to the current five conditions that are included in the D-KEFS to allow for comparisons with motor and processing speed (Lezak et al., 2004). According to Lezak and colleagues (2004), the shifting condition of trails is found to correlate highly with measures of cognitive flexibility such as the Wisconsin Card Sorting Test providing further evidence for adequate construct validity.

Control of Retrieval from Long-Term Memory

Control of retrieval from long-term memory was measured with the D-KEFS Verbal Fluency test (Delis, Kaplan, & Kramer, 2001). Verbal Fluency is a variation of the Controlled Oral Word Association Test (COWAT; Benton & Hamsher, 1989; Eslinger, Damasio, & Benton, 1984) which has a long history of use in neuropsychology practice. This measure requires participants to retrieve words from long-term memory based on a specific response set. As with the Trail-Making Test, there are several conditions. In the

first condition, Letter Fluency, the participant is required to list as many words as they can that begin with a given letter (e.g., F, A, or S). The second condition is Category Fluency in which the child is asked to list words in a specific category (e.g. animals). In the third condition, Category Switching, the child again lists words, but must alternate the category that the word belongs to (e.g. furniture and boys names). For each condition, the time limit is 60 seconds. Additional guidelines are that the words cannot be a proper noun and the participant cannot simply change the ending of a word (i.e. the participant cannot say both runs and running). These rules apply for all conditions of the test. The score for each condition is the total number of correct words the participant is able to produce within the 60 second time limit. Additional scores include repetition errors and set-loss errors.

Internal consistency for the D-KEFS verbal fluency measure ranges from .68 to .81 for ages 8 to 19 (Delis, Kaplan, & Kramer, 2001). Lezak and colleagues (2004) report that successful performance on verbal fluency measures relies heavily on successful retrieval from semantic memory indicating adequate construct validity for control of retrieval from long-term memory.

In terms of construct validity for verbal fluency tasks, Raskin and Rearick (1996) found that individuals with acceleration-deceleration closed-head injury, a population known to demonstrate executive deficits similar to ADHD, made more set-loss errors on verbal fluency tasks than controls. Their performance on verbal fluency also correlated with recall scores on memory measures establishing a relationship between verbal fluency and memory processes. Verbal fluency performance also correlated with perseverative errors on the Wisconsin Card Sorting Test confirming an executive control

component of verbal fluency. These results indicate that both memory and executive processes are related to verbal fluency performance, establishing construct validity for D-KEFS verbal fluency as a measure that taps both executive control and retrieval processes.

Percent combined set-loss errors standard scores were utilized as the measure of control of retrieval from long-term memory. Set-loss errors are defined as any word stated by the examinee that violates a rule of the task (Delis, Kaplan, & Kramer, 2001). Chertkow and Bub (1990) determined that deficient performance on verbal fluency measures in the Alzheimer's population were related to two deficits: (a) deterioration of the semantic store or (b) deterioration of retrieval processes. The number of words retrieved in the verbal fluency task appears to be dependent upon the capacity of the semantic store; whereas, errors on the task appear to specifically reflect difficulties with the retrieval process (Chertkow & Bub, 1990). Errors on verbal fluency are also more sensitive to increases in working memory load as compared to total words (Azuma, 2004), indicating a greater likelihood for that score to be indicative of central executive functioning. On the D-KEFS verbal fluency test, a violation of the task rules is therefore an indication that the child cannot control their retrieval processes to the extent necessary to follow the task rules. The standard score of the percent of these errors is an indication of how many set-loss errors the child made relative to their own retrieval and relative to their same age peers. The score is therefore an indication of the child's capacity for controlling the information that they retrieve from their long-term memory based on a given set of rules.

Though there is sufficient evidence to establish a relationship between verbal fluency and both executive and memory processes and between errors on verbal fluency and difficulties with retrieval processes, specific evidence for establishing construct validity of verbal fluency set-loss errors as an appropriate measure for control of retrieval from long-term memory remains limited. This is primarily the result of limited research available for the construct control of retrieval. As the limited evidence in the empirical literature does not provide sufficient basis for specific hypothesis formation, this variable will be treated as exploratory.

Research Design

This study used a correlational research design. In this study, the independent variables were ADHD Inattentive symptoms, ADHD Hyperactive, and ADHD Impulsive symptoms as operationalized by the Attention Deficit Disorders Evaluation Scale (McCarney, 1989). Mediating variables were short-term memory, sustained attention, selective attention/inhibition, shifting attention, and control of retrieval from long-term memory. Short-term memory was operationalized as Digits Forward scaled scores on the WISC-IV (Wechsler, 2003). Sustained attention was operationalized as omission errors T-scores on the Conners' CPT II (Conners, 2002). Selective attention/inhibition was measured as commission errors T-scores on the Conners' CPT II (Conners, 2002). Both of these T-scores indicate participants' scores relative to age and gender based norms. Shifting attention was operationalized as D-KEFS Number-Letter Sequencing vs. Number Sequencing Scaled Score (Delis, Kaplan, & Kramer, 2001). This contrast score is the difference between Number Sequencing and Number-Letter Sequencing scores and is an indication of the difference in the child's performance when sequencing and when

sequencing and shifting thereby isolating the switch cost or the time added to a child's performance when required to shift their attention. Control of retrieval from long-term memory was measured as the percent of set-loss errors standard score on D-KEFS verbal fluency (Delis, Kaplan, & Kramer, 2001). The dependent variable in this study was working memory performance, operationalized as WISC-IV Letter-Number Sequencing scaled scores (Wechsler, 2003).

Procedures

Participants were taken from a larger clinical database of children that were referred for neuropsychological assessment at an urban outpatient neuropsychological assessment clinic. Inclusion criteria was completion of all neuropsychological and behavioral measures included in the research design. Exclusionary criteria included diagnosis of mental retardation or any autism spectrum disorder. Because item-level data was not provided to the researcher as part of the clinical database, it was not possible to calculate score reliabilities for the current sample. As previously discussed, the measures utilized in the current study have strong psychometric properties. The inability to calculate sample specific reliabilities is therefore not a concern.

Data Analysis

Descriptive Statistics and Outliers

All analyses were completed using SPSS version 13.0. Means and standard deviations for each variable were calculated. The ADHD symptom variables and mediator variables were tested for outliers using Mahalonobis Distance compared to chi-square critical values. This statistic was chosen because it measures multivariate outliers rather than univariate (Stevens, 2002). Residuals for the dependent variable, working

memory, were also examined to ensure that they are normally distributed. Residuals that are greater than positive or negative 3 will be considered outliers (Stevens, 2002).

Influential data points were detected with Cook's Distance and DFBETAS. Cook's Distance is an indication of a case's influence on both the predictors and the dependent variable and DFBETAS indicate datapoints that have an impact on specific regression coefficients (Stevens, 2002). If a case was an outlier based on Mahalanobis Distance or standardized residuals and influential based on Cook's Distance greater than 1 or DFBETAS greater than the absolute value of 2, that case was deleted from the analysis.

Assumptions for Regression Analyses

Normality, Linearity, and Homoscedasticity

To evaluate whether each of the assumptions of normality, linearity, and homoscedasticity are satisfied, plots of residuals were examined. The normality of errors assumption was evaluated by examining a histogram of residuals. If this assumption is satisfied, then the distribution of residuals should form a normal curve (Stevens, 2002). If this assumption was violated for any variable, appropriate transformation of that variable to normalize the distribution would have occurred. Scatterplots of residuals were also examined to determine if the relationships among variables are linear. Scatterplots of standardized residuals compared to predicted values were examined. If this assumption is satisfied, then the datapoints should scatter randomly around a horizontal line. If the scatter is not random, e.g. a curvilinear shape, then the assumption of linearity would have been violated (Stevens, 2002). If this assumption had been violated, the data would have been transformed or an alternative estimation method would be used as is determined to be appropriate. To determine if variance is consistent across variables,

scatterplots of residuals around the regression line were examined. Datapoints should be equally distributed around the regression line indicating that variance is consistent, or that the assumption of homoscedasticity is satisfied. If this assumption had been violated then the data would be transformed to meet the requirements of this assumption.

Independence

The independence assumption requires that responses of participants are not related. As each participant in the database was tested individually and did not have contact with any other participants, this assumption is satisfied in the current analyses.

Multicollinearity

Multicollinearity is defined as high intercorrelations among predictor variables (Stevens, 2002). In order to determine if multicollinearity was an issue with the predictors in this study, two methods were used. First, bivariate correlations among the predictors were examined to determine the intercorrelations among predictors. Pearson correlations were examined between the independent variable and mediation variables and among the mediation variables. Significant correlations were expected between the independent variables and the mediators; however, significant correlations were not expected among the mediation variables. In the literature, correlations among these constructs were found to be low to moderate, ranging from .21 to .57 (Berlin, Bohlin, & Rydell, 2003; Swanson, Mink, & Bocian, 1999; Tsal, Shalev, & Mevorach, 2005). Correlations above .80 were considered problematic (Stevens, 2002). Second, the variance inflation factor was determined for each predictor. The variance inflation factor determines the squared multiple correlation of regressing all other predictors on each individual predictor (Stevens, 2002). Variables with a variance inflation factor of 10 or

greater were considered problematic. If the multicollinearity assumption for these variables was not satisfied, removal or combination of variables as well as alternative estimation methods to least squares estimation were considered (Stevens, 2002).

Research Question One Analysis

To verify or refute the theoretical and empirical evidence that four fractionated processes of the central executive explain unique variance in working memory performance, the four central executive processes were included as predictors in a multiple regression equation with working memory performance as the dependent variable. The predictors were sustained attention, selective attention/inhibition, shifting attention, and control of retrieval from long-term memory. Short-term memory was included as a covariate in the equation to ensure that the central executive variance in the working memory task is isolated. The results of this analysis also determined potential mediators for research question three. A mediation model was completed for each central executive process that is found to explain unique variance in working memory.

Research Question Two Analysis

In order to determine which domains of ADHD symptoms explain working memory performance, a multiple regression analysis was conducted with ADHD Inattentive, ADHD hyperactive, and ADHD impulsive symptoms as the predictor variables and working memory performance as the dependent variable. It was hypothesized that inattentive symptoms would account for the most variance in working memory performance and that hyperactive and impulsive symptoms would not account for additional variance in working memory after inattentive symptoms were accounted for. The outcome of this analysis was planned to determine the independent variable in

the analyses for research question three. If only inattentive symptoms accounted for unique variance in working memory performance as expected, inattentive symptoms would be the independent variable. If a combination of inattentive, hyperactive, and impulsive symptoms explained working memory variance, the mediation models for research question three would be completed first with inattentive symptoms as the independent variable followed by hyperactive symptoms and/or impulsive symptoms as the independent variable.

Additional Assumptions for Research Question Three

Measurement error

An additional statistical assumption required for mediation models is that there is no measurement error in the mediation variables. This was a potential problem in the current study as measures of executive functions typically have a higher rate of measurement error than other cognitive variables. The reliabilities for mediation variables in this study range from .59 to .94 indicating potential for error variance in the scores. Baron and Kenny (1986) acknowledge that this assumption is typically not satisfied when using internal, psychological variables. When this assumption is not satisfied, it is more difficult to find a significant mediator due to underestimation of the indirect effect and overestimation of the direct effect. This assumption was considered when interpreting results of the mediation models. Due to measurement error in the mediation variables, it is likely that the relationship between ADHD symptoms and working memory was overestimated and the mediation effect of the central executive variables on that relationship were underestimated.

Causation

A second assumption required for mediation analysis is that the dependent variable cannot cause the mediator. In order for a causal relationship to be established, the causal variable must precede the other variable in time and experimental methods must be used. Based on current available research, causal relationships have not been experimentally established among the variables in the current study. It is hypothesized that executive processes have a top-down effect on the working memory system (Baddeley, 2003). This suggests that the causal relationship, if established, would be in the opposite direction of the causation assumption, with the mediator causing the dependent variable. In addition, when examining the development of executive functions, inhibition develops earlier than working memory (P. Anderson, 2002; V. Anderson, 1998), again providing support that working memory does not cause the mediating variables. Based on the lack of evidence for a definitive causal relationship among the variables included in the current analyses and because evidence appears to suggest a potential causal relationship from the mediators to the dependent variable, the assumption that the dependent variable cannot cause the mediation variable was assumed to be satisfied for the mediation analyses in the current study.

Expected multicollinearity

Because the current study utilized mediation models, it was assumed that the independent variable (ADHD symptoms) caused the mediation variables (sustained attention, selective attention/inhibition, shifting attention, and control of retrieval from long-term memory). Based on this assumption, it was expected that the independent variable and the mediation variables be correlated. This leads to expected violation of the multicollinearity assumption (Baron & Kenny, 1986). Because of this violation, power

was reduced in the final regression equation in which both the independent variable and the mediation variable were regressed on the dependent variable. This decrease in power means that the effects of the mediator may have been underestimated and effects of the independent variable may have been overestimated. To remedy this situation, Baron and Kenny (1986) suggest examining the size of the coefficients in addition to the significance to monitor for the overestimation of the effect of the independent variable.

Research Question Three Analyses

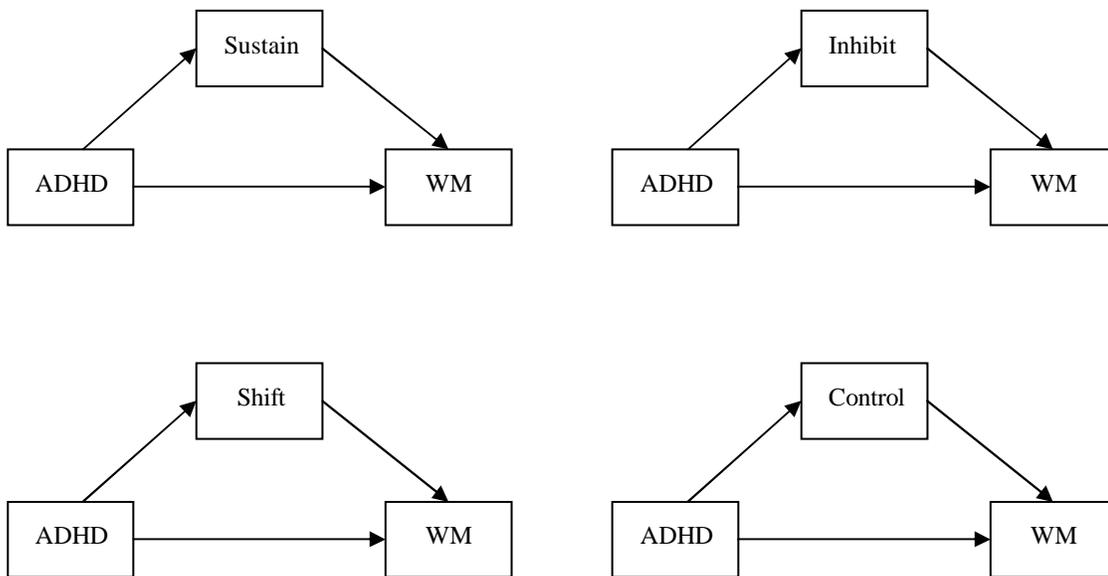
To test which central executive processes mediate the relationship between ADHD symptoms and working memory performance, the procedure for testing mediation established by Baron and Kenny (1986) was used. First, ADHD symptoms, based on results of research question one, were regressed on sustained attention using simple regression. Next, ADHD symptoms were planned to be regressed on working memory using simple regression. Next, sustained attention was planned to be regressed on working memory. Finally, both ADHD symptoms and sustained attention were regressed on working memory using multiple regression.

The indirect effects of the mediation were then calculated using Sobel's (1982) procedure. In this procedure the indirect effects were the product of the unstandardized regression coefficients for (a) the independent variable (ADHD symptoms) regressed on the mediator (e.g. sustained attention) and (b) the independent variable and the mediation variable regressed on the dependent variable [$b_{\text{indirect}} = (b_2)(b)$].

Once the indirect effects had been calculated, the significance of the mediation could be tested to determine if the indirect effect was significantly different from zero. First the standard error of the indirect effect was calculated [$se_{ab} = \sqrt{(b^2 s_a^2 + a^2 s_b^2 + s_a^2 s_b^2)}$]

(Baron & Kenny, 1986). The indirect effect was then divided by this standard error of the indirect effect to obtain a z value ($z_{ab} = b_{\text{indirect}}/se_{ab}$). This z value is compared to the critical value 1.96 to determine significance (MacKinnon & Dwyer, 1993). These steps were repeated as appropriate for each mediator as illustrated in Figure 1.

Figure 1. Diagrams of potential models of central executive processes mediating the relationship between ADHD symptoms and working memory performance.



Note. ADHD = ADHD symptoms (inattention, hyperactivity, or impulsivity); WM = WISC-IV Letter-Number Sequencing; Sustain = Conners' CPT II Omission errors; Inhibit = Conners' CPT II Commission errors; Shift = D-KEFS Number-Letter Sequencing vs. Number Sequencing Scaled Score; Control = D-KEFS verbal fluency set-loss errors standard score

Bootstrapping

There are criticisms of the Baron and Kenny (1986) and Sobel (1982) approaches to testing mediation. Results of simulation studies (MacKinnon et al., 2002) indicate that the Baron and Kenny (1986) procedure results in low statistical power and type I error rates that are lower than expected in simulation studies unless the effect is large. In addition, the Sobel (1982) procedure is designed for large sample sizes. In smaller sample sizes, the standard error distribution for the Sobel procedure tends to be skewed. Sobel's (1982) procedure assumes normality of this standard error distribution due to the tendency of distributions to normalize as sample sizes get larger (Shrout & Bolger, 2002). Ignoring this skew in smaller samples leads to reduced power to detect mediation effects. Bootstrapping for the standard error is suggested when testing for mediation effects in smaller sample sizes (MacKinnon et al., 2002; Preacher & Hayes, 2004; Shrout & Bolger, 2002; Wu & Zumbo, 2007). Based on these recommendations and the relatively small sample size in the current study, bootstrapping of the standard error was utilized in the current study to test the mediation effect. Procedures for bootstrapping to test mediation effects outlined by Preacher and Hayes (2004) were followed. A 95% confidence interval was utilized to determine if the mediation effect could be zero.

CHAPTER IV

RESULTS

In the current chapter, results of analyses described in the previous chapter will be presented including descriptive statistics; preliminary analyses; regression analyses examining relationships between central executive processes, ADHD symptoms, and working memory; and mediation analyses following the steps of Baron and Kenny (1986) with bootstrapping for the standard error (MacKinnon et al., 2002; Preacher & Hayes, 2004; Wu & Zumbo, 2007).

Descriptive Statistics

From the clinic-referred database, 85 children satisfied the sample criteria for age (8 to 16) and did not have an exclusionary diagnosis of mental retardation or any autism spectrum disorder. Mean age for the sample was 11.47 (2.57). In terms of race, 85 percent of the sample was Caucasian and 15 percent was African-American. In terms of gender, the sample was 65 percent male and 35 percent female. Eighty-four percent of the sample was right-handed, 11 percent was left-handed, and 5 percent reported mixed-handedness. Missing data resulting from limitations of the clinical database was handled by pairwise deletion. Rather than removing all participants with any missing data as with listwise deletion, in pairwise deletion, only those participants with missing data related to each analysis are deleted resulting in the maximum possible sample size for each analysis (Kline, 2005). Means and standard deviations for each variable are reported in Table 1.

Table 1.

Means and standard deviations of study variables.

Variable	Mean	SD	Std. Score Range	n
Working Memory	8.41	0.42	1 to 19	71
Short-term Memory	8.45	0.37	2 to 14	69
Sustained Attention	52.79	1.27	38 to 87	80
Inhibition	52.54	0.98	28 to 71	82
Shifting	8.47	0.39	1 to 15	49
Retrieval from LTM	10.33	0.58	1 to 14	48
ADHD Inattentive	6.82	0.46	0 to 15	76
ADHD Impulsive	8.17	0.43	0 to 16	75
ADHD Hyperactive	8.59	0.41	0 to 16	75

Note. SD = Standard Deviation; Inhibition = Selective Attention/Inhibition; Shifting = Shifting Attention; LTM = Long-term Memory; ADHD = Attention-Deficit/Hyperactivity Disorder

Preliminary Analyses

Results of Pearson bivariate correlations between study variables are reported in Table 2. Significant correlations were found between short-term memory and working memory, short-term memory and sustained attention, and sustained attention and working memory. ADHD inattentive symptoms, hyperactive symptoms, and impulsive symptoms also correlated significantly. This intercorrelation will be addressed in results for research question two. None of the domains of ADHD symptoms correlated significantly with

working memory; however, ADHD hyperactive and impulsive symptoms correlated significantly with short-term memory.

Table 2

Pearson correlation results among study variables.

	1	2	3	4	5	6	7	8	9
1. WM	1	--	--	--	--	--	--	--	--
2. STM	0.25*	1.00	--	--	--	--	--	--	--
3. Sustained	-0.39**	-0.31*	1.00	--	--	--	--	--	--
4. Inhibition	0.01	0.12	0.22*	1.00	--	--	--	--	--
5. Shifting	0.19	0.06	-0.40**	-0.01	1.00	--	--	--	--
6. Retrieval	0.36*	0.37*	-0.09	-0.07	0.01	1	--	--	--
7. Inattentive	0.14	0.12	-0.07	-0.11	-0.04	-0.06	1	--	--
8. Impulsive	0.18	0.26*	-0.18	-0.09	-0.004	-0.07	0.68**	1	--
9. Hyperactive	0.15	0.32*	-0.34*	-0.08	0.01	-0.06	0.62**	0.75**	1

Note. * $p < .05$; ** $p < .01$; WM = Working Memory; STM = Short-term Memory; Sustained = Sustained Attention; Inhibition = Selective Attention/Inhibition; Shifting = Shifting Attention; Retrieval = Control of Retrieval from Long-term Memory; Inattentive = ADHD Inattentive Symptoms; Impulsive = ADHD Impulsive Symptoms; Hyperactive = ADHD Hyperactive Symptoms

Analyses for Statistical Assumptions

The dataset was examined for outliers. Two cases were outliers based on Mahalanobis Distance values but those cases were not influential based on DFBETA or Cook's Distance values according to previously stated criteria. One datapoint for the sustained attention variable was removed from analyses as it was an impossible value for

that variable and was determined to be a data-entry error. To determine if the assumption of normality of errors was satisfied, a histogram of residuals was examined. Based on the approximately normal distribution of these residuals for each regression, this assumption was determined to be satisfied. These histograms are included with each analysis below. The assumption of linearity was also satisfied based on the random pattern of standardized residuals around a horizontal line for each regression equation. These scatterplots are presented with each analysis below. The homoscedasticity assumption was also satisfied based on the uniform scatter of plotted residuals around each regression line. These plots are also included below with each analysis.

Based on low intercorrelations among predictor variables and variance inflation factor values lower than the previously stated maximum value, the multicollinearity assumption is satisfied for research question one. Based on the high inter-correlations among predictor variables for research question two (ADHD Inattentive, ADHD hyperactive, and ADHD impulsive symptoms), the assumption of multicollinearity is violated for this analysis. Because of this violation, all subsequent analyses will include only ADHD hyperactive symptoms.

Central Executive Processes and Working Memory

To answer research question one, determining which processes of the central executive (sustained attention, selective attention/inhibition, shifting attention, and/or control of retrieval from long-term memory) explain variance in working memory performance, multiple regression analyses were completed. It was hypothesized that each of the four processes of the central executive would explain unique variance in working memory performance. Due to the difference in sample size between participants that had

and had not been given the D-KEFS, a separate regression equation was necessary for those variables. Both regression equations included short-term memory as a covariate and working memory as the dependent variable. In the first equation, sustained attention and selective attention/inhibition were included as independent variables. Shifting attention and control of retrieval from long-term memory were included in the second equation as independent variables.

When short-term memory, sustained attention, and selective attention/inhibition were regressed on working memory all assumptions included normality of errors (Figure 2), Linearity (Figure 3), and Homoscedasticity (Figure 4) were satisfied.

Figure 2. Normal distribution of residuals for dependent variable working memory with short-term memory, sustained attention, and selective attention/inhibition as predictors.

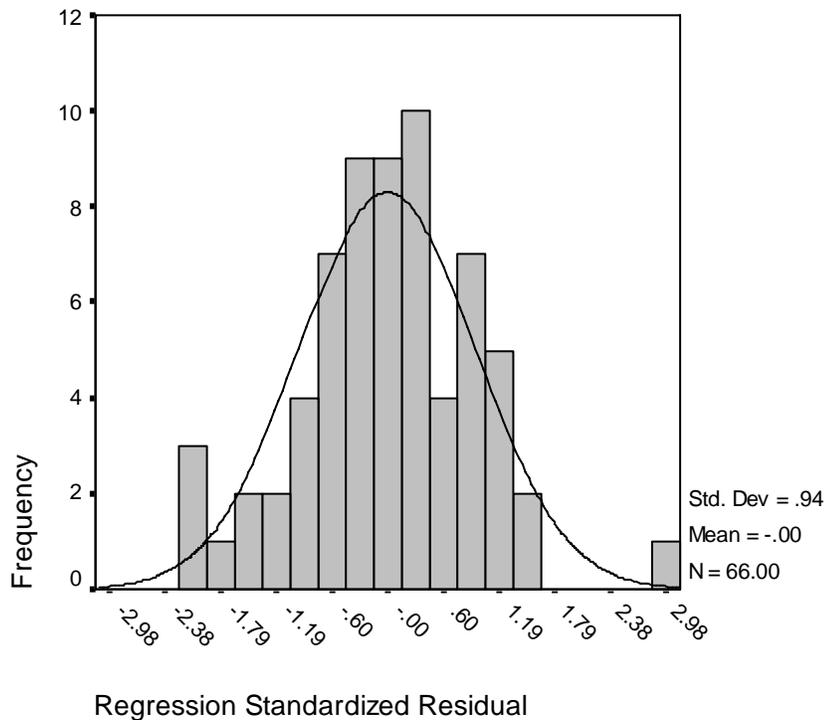


Figure 3. Scatterplot of standardized residuals showing satisfaction of linearity assumption for the dependent variable working memory.

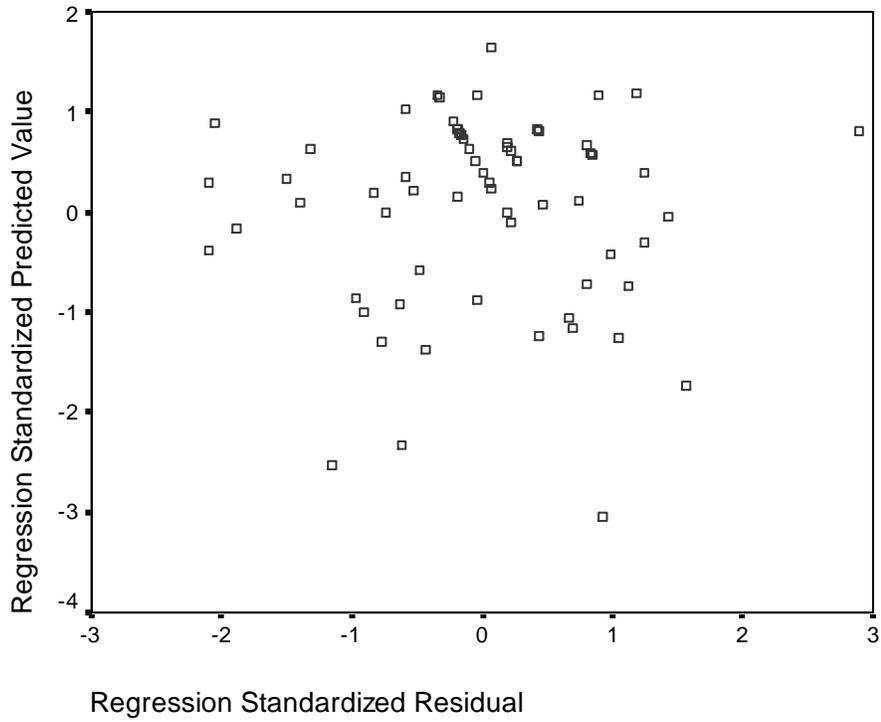
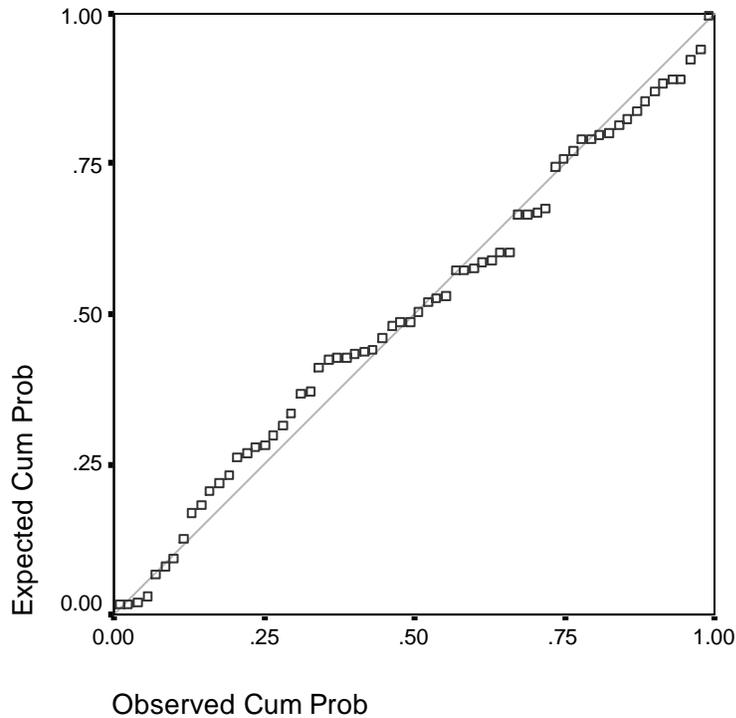


Figure 4. Scatterplot of residuals around regression line for dependent variable working memory satisfying homoscedasticity assumption.



Results of regression analysis indicates that short-term memory contributes unique variance to working memory performance. The null hypothesis that there is no relationship between short-term and working memory is therefore rejected, $F(1, 65) = 5.12, p < .05$. Consistent with previously reported correlations, short-term memory accounts for 7 percent of the variance in working memory ($R = .27, \hat{y} = .30x_{stm} + 5.85$). When sustained attention and selective attention/inhibition are added to the model, the null hypothesis is again rejected, $F(3, 65) = 4.38, p < .05$. The model with short-term memory, sustained attention, and selective attention/inhibition as predictors accounted for 18 percent of variance in working memory performance ($R = .42, \hat{y} = .18x_{stm} - .11x_{sustain} + .03x_{inhibit} + 10.78$). With respect to short-term memory, sustained attention and

selective attention/inhibition accounted for an additional 10 percent of variance in working memory (R^2 change = .10). Part correlations, indicating the unique variance accounted for by each independent variable, show that after accounting for short-term memory variance sustained attention contributed an additional 10 percent of working memory variance ($\beta = -.11$, $p < .01$, part = .32) whereas selective attention/inhibition contributed 1 percent of additional variance ($\beta = .03$, $p = .46$, part = .08). As sustained attention contributes unique variance to working memory performance, it will be included in subsequent mediation analyses. Post-hoc power analysis based on a medium effect size ($f^2 = .21$) indicates a power of .87.

Table 3

Regression analysis with short-term memory, sustained attention, and selective attention/inhibition regressed on working memory.

	B	SE B	β	t	p
Model 1					
STM	0.3	0.13	0.27	2.26	0.03
Model 2					
STM	0.18	0.14	0.16	1.28	0.21
Sustained	-0.11	0.04	-0.35	-2.75	0.01
Inhibition	0.03	0.05	0.09	0.75	0.46

Note. SE = Standard Error; STM = Short-term Memory; Sustained = Sustained Attention; Inhibition = Selective Attention/Inhibition

This same procedure was completed with the other central executive variables, shifting attention and control of retrieval from long-term memory. Assumptions of normality of errors (Figure 5), linearity (Figure 6) and homoscedasticity (Figure 7) were also satisfied for this regression equation.

Figure 5. Normal distribution of residuals for dependent variable working memory with short-term memory, shifting attention, and control of retrieval as predictors.

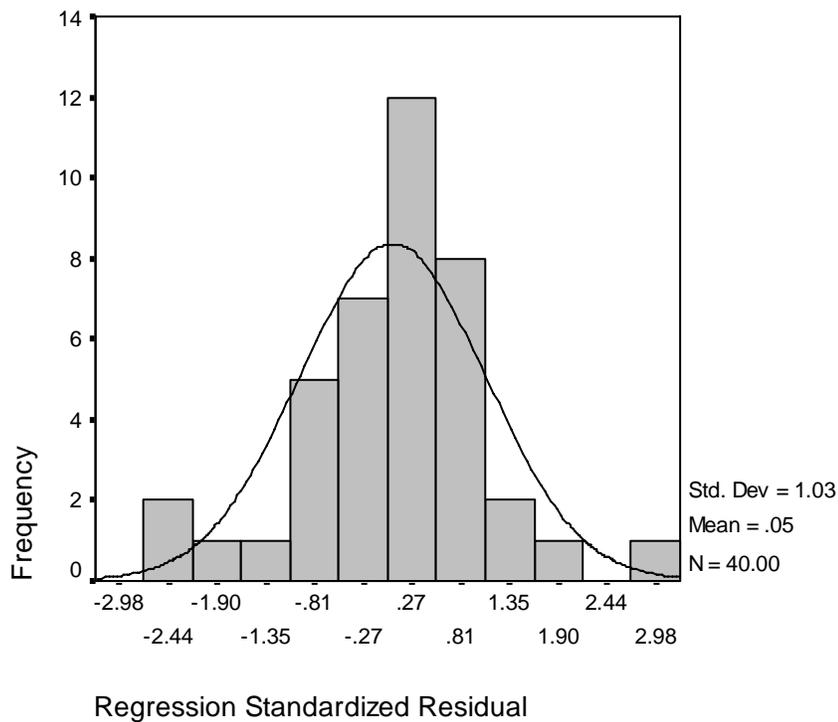


Figure 6. Scatterplot of standardized residuals showing satisfaction of linearity assumption for dependent variable working memory.

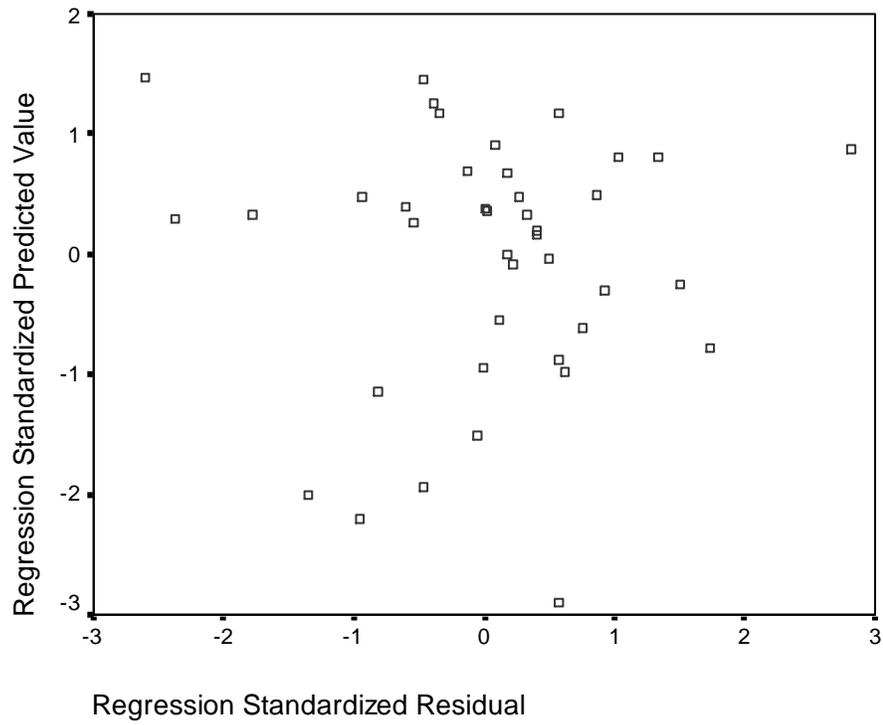
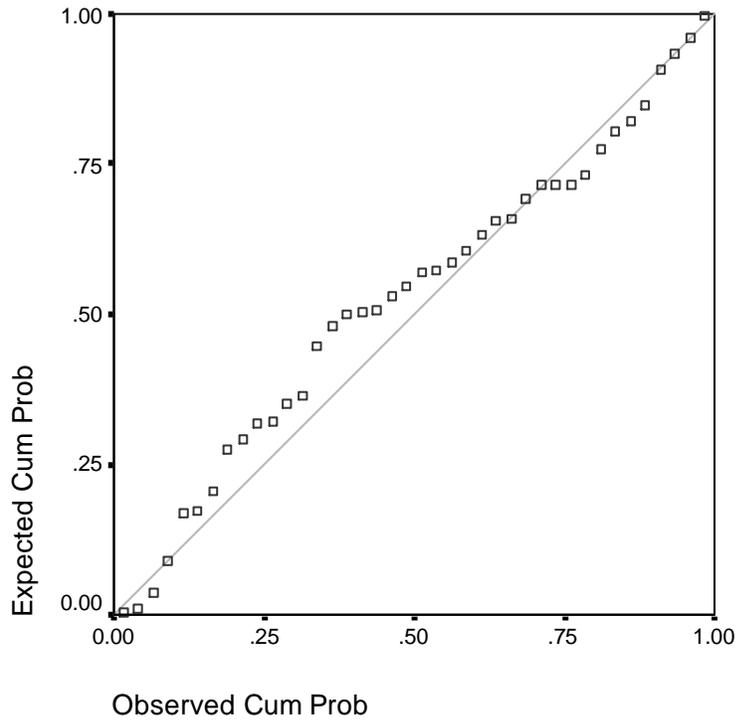


Figure 7. Scatterplot of residuals around regression line for dependent variable working memory satisfying homoscedasticity assumption.



The combination of short-term memory, shifting attention, and control of retrieval from long-term memory did not account for a significant amount of variance in working memory ($F(2, 39) = 2.54, p = .07$). Though 18 percent of total working memory variance was explained by these variables, the null hypothesis was accepted for this equation. Post-hoc power analysis with a medium effect size ($f^2 = .21$) indicates that power is .62 for this equation which may not have been sufficient to detect interrelationships among these variables.

Table 4

Regression analysis with short-term memory, shifting attention, and control of retrieval from long-term memory regressed on working memory.

	B	SE B	β	t	p
Model 1					
STM	0.36	0.19	0.30	1.93	0.06
Model 2					
STM	0.23	0.20	0.19	1.16	0.26
Shifting	0.19	0.20	0.14	0.94	0.35
Retrieval	0.24	0.15	0.27	1.68	0.10

Note. SE = Standard Error; STM = Short-term Memory; Shifting = Shifting Attention; Retrieval = Control of Retrieval from Long-term Memory

ADHD Symptoms and Working Memory

To answer which symptom domain of ADHD (hyperactive, impulsive, or inattentive) has the strongest relationship with working memory performance, a multiple regression was planned with each ADHD symptom domain as independent variables and working memory as a dependent variable. It was hypothesized that (a) inattentive symptoms of ADHD would have a stronger relationship with working memory performance as compared to hyperactive or impulsive symptoms, (b) hyperactive symptoms would not account for additional working memory variance after accounting for variance in inattentive symptoms, and (c) impulsive symptoms would not account for

additional working memory variance after accounting for variance in inattentive symptoms.

As previously noted, results of Pearson correlations indicate there are significant correlations among the ADHD symptom domains (see Table 2). These intercorrelations among the independent variables indicate that the assumption of multicollinearity is violated for this regression equation. Further examination of bivariate correlations indicates that none of the symptom domains of ADHD correlate with working memory indicating that these variables do not contribute unique variance to working memory performance.

Mediation by Central Executive Processes

The goal of research question three was to determine which process(es) of the central executive mediate the relationship between symptoms of ADHD and working memory performance; however, based on results of question two, in this sample symptoms of ADHD do not contribute unique variance to working memory performance. Based on results of preliminary correlational analyses, short-term memory does show a relationship with symptoms of ADHD. Mediation analyses were then completed as planned with short-term memory as the dependent variable rather than working memory to explain this relationship. It was hypothesized that sustained attention would significantly mediate the relationship between symptoms of ADHD and short-term memory.

Prior to completing the mediation analysis, an additional regression analysis was completed with sustained attention and selective attention/inhibition as predictors and short-term memory as the dependent variable in order to confirm which central executive

processes contribute unique variance to short-term memory. As previously noted, all assumptions including normality of errors (Figure 8), linearity (Figure 9), and homoscedasticity (Figure 10) were satisfied.

Figure 8. Normal distribution of residuals for dependent variable short-term memory with sustained attention and selective attention/inhibition as predictors.

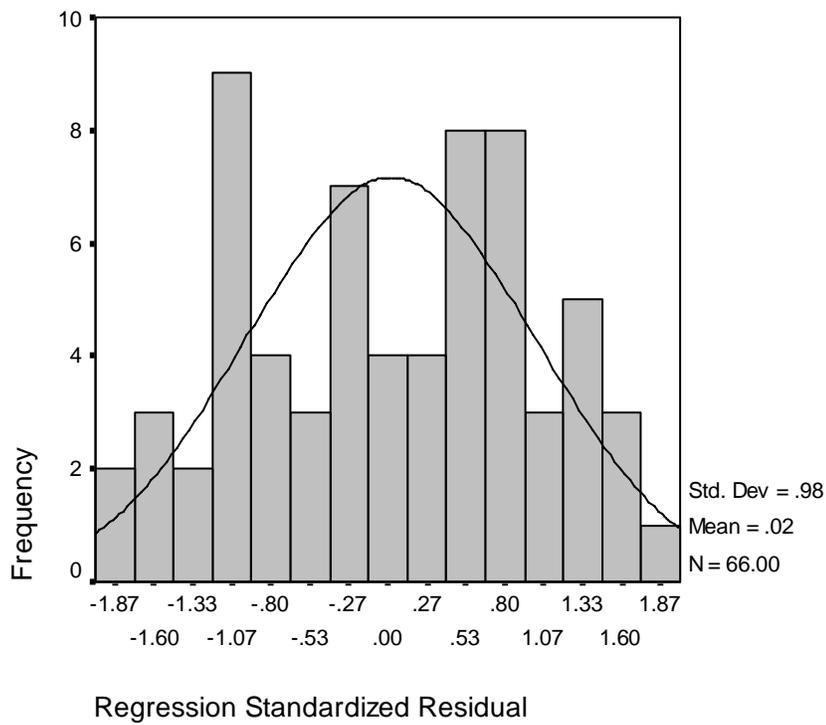


Figure 9. Scatterplot of standardized residuals showing satisfaction of linearity assumption for dependent variable short-term memory.

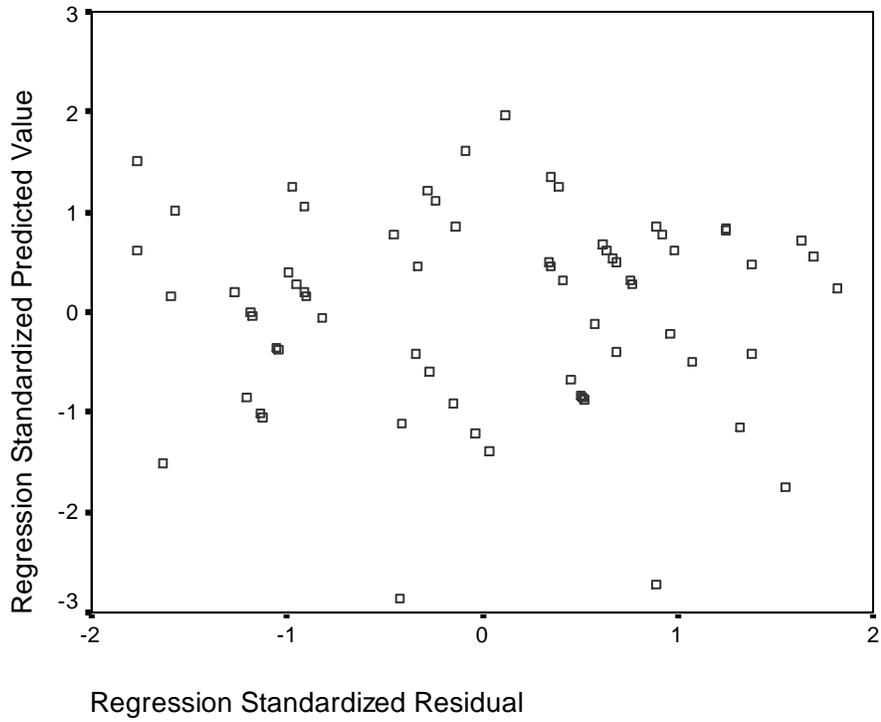
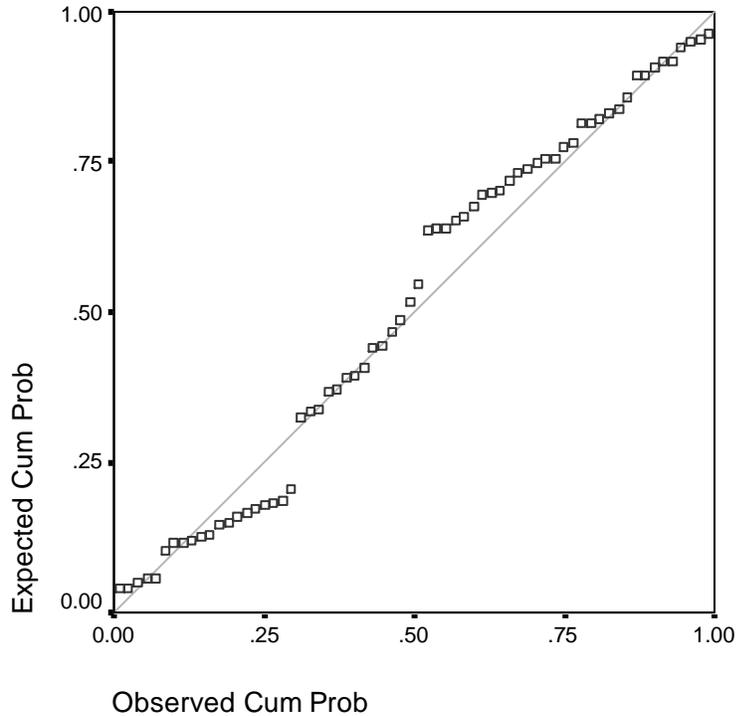


Figure 10. Scatterplot of residuals around regression line for dependent variable short-term memory satisfying homoscedasticity assumption



The null hypothesis was again rejected for this equation indicating that these central executive processes contribute unique variance to short-term memory, $F(2, 65) = 4.80, p < .05$. Post-hoc power analysis with a medium effect size ($f^2 = .15$) indicates power of .79 for this equation. Consistent with working memory results, the combination of sustained attention and selective attention/inhibition explained 13 percent of variance in short-term memory ($R = .36, \hat{y} = -.10x_{\text{sustain}} + .07x_{\text{inhibit}} + 9.91$). Sustained attention contributed 12 percent of the total variance ($\beta = -.10, p < .01, \text{part} = -.34$), whereas selective attention/inhibition contributed 4 percent ($\beta = .07, p > .10, \text{part} = .19$). Sustained attention will therefore be included in the mediation analysis.

Table 5

Regression analysis with sustained attention and selective attention/inhibition regressed on short-term memory.

	B	SE B	β	t	p
Sustained	-0.1	0.03	-0.35	-2.93	0.01
Inhibition	0.07	0.04	0.2	1.64	0.11

Note. SE = Standard Error; Sustained = Sustained Attention; Inhibition = Selective Attention/Inhibition

Following the procedures outlined by Baron and Kenny (1986), the independent variable, hyperactive symptoms, was first regressed on the dependent variable short-term memory. Assumptions of normality of errors (Figure 11), linearity (Figure 12), and homoscedasticity (Figure 13) were satisfied for this regression.

Figure 11. Normal distribution of residuals for hyperactive symptoms regressed on short-term memory.

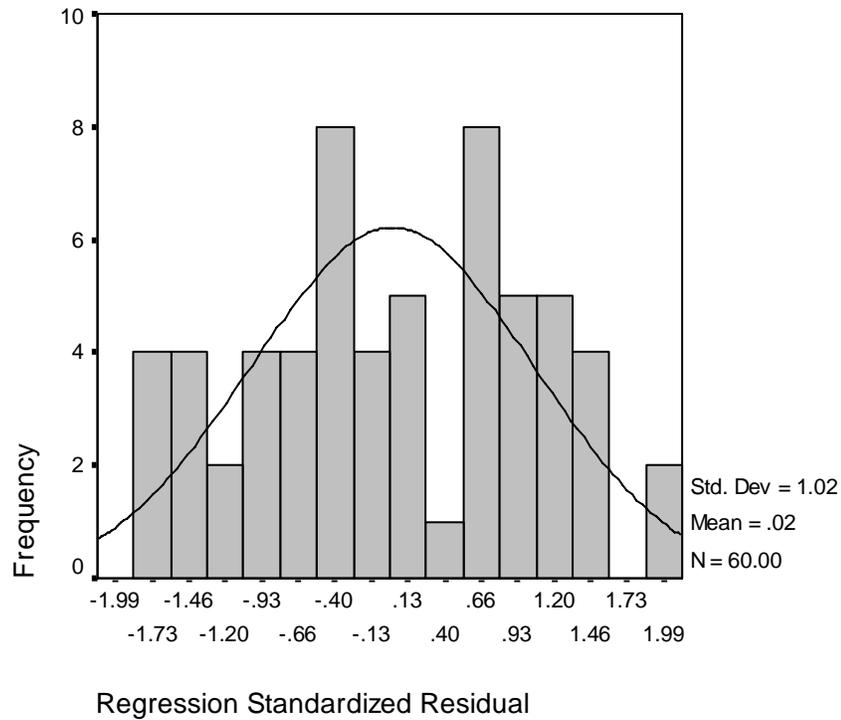


Figure 12. Scatterplot of standardized residuals showing satisfaction of linearity assumption for dependent variable short-term memory.

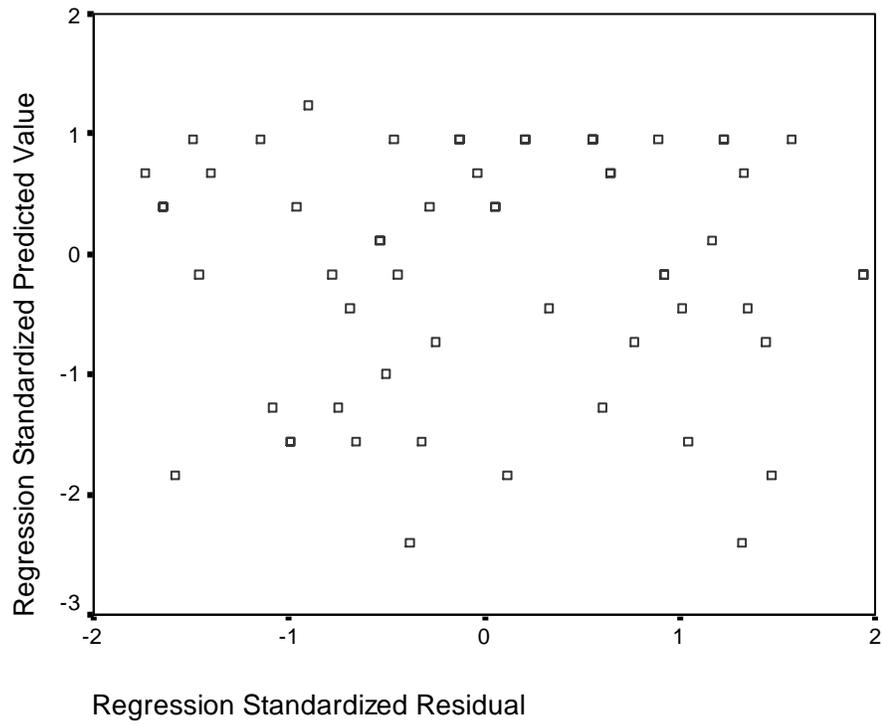
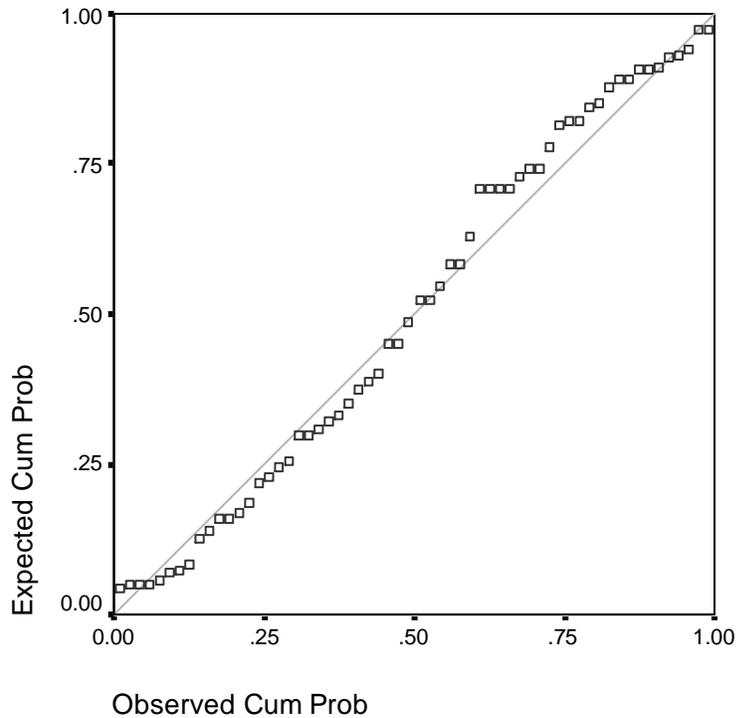


Figure 13. Scatterplot of residuals around regression line for dependent variable short-term memory satisfying homoscedasticity assumption



Satisfying the first criterion of Baron and Kenny's (1986) requirements for mediation, the null hypothesis was rejected for this regression equation, $F(1,59) = 6.40$, $p < .01$. Sustained attention explained 10 percent of the variance in short-term memory ($\beta = .271$, $p < .02$, $\text{part} = .315$). Based on a small effect size ($f^2 = 0.11$), power for this analysis is 0.71.

The second step of the mediation sequence requires the independent variable, hyperactive symptoms to be regressed on the mediation variable, sustained attention. Normality of errors (Figure 14), linearity (Figure 15), and homoscedasticity (Figure 16) were again satisfied.

Figure 14. Normal distribution of residuals for hyperactive symptoms regressed on sustained attention.

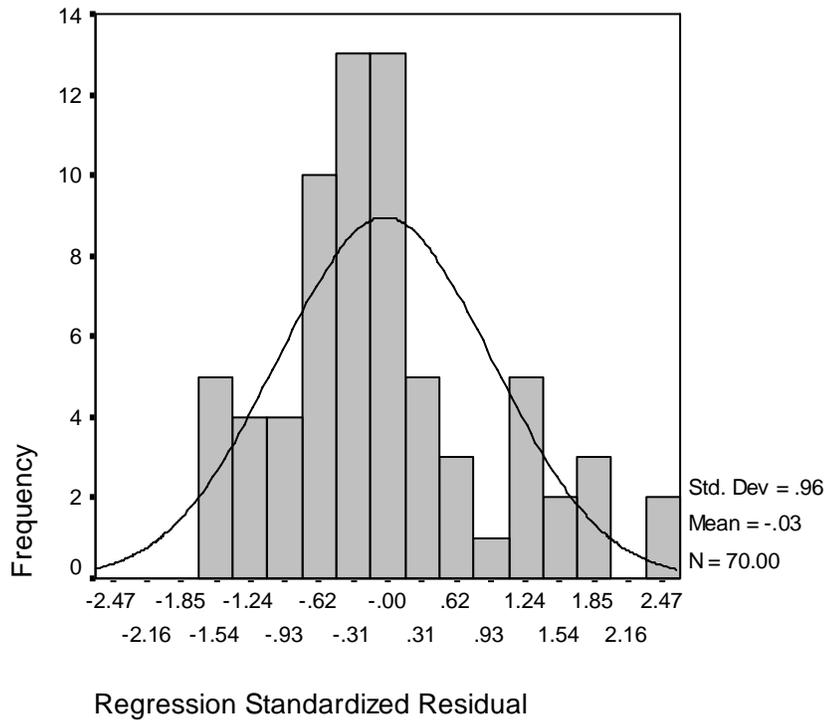


Figure 15. Scatterplot of standardized residuals showing satisfaction of linearity assumption for dependent variable sustained attention.

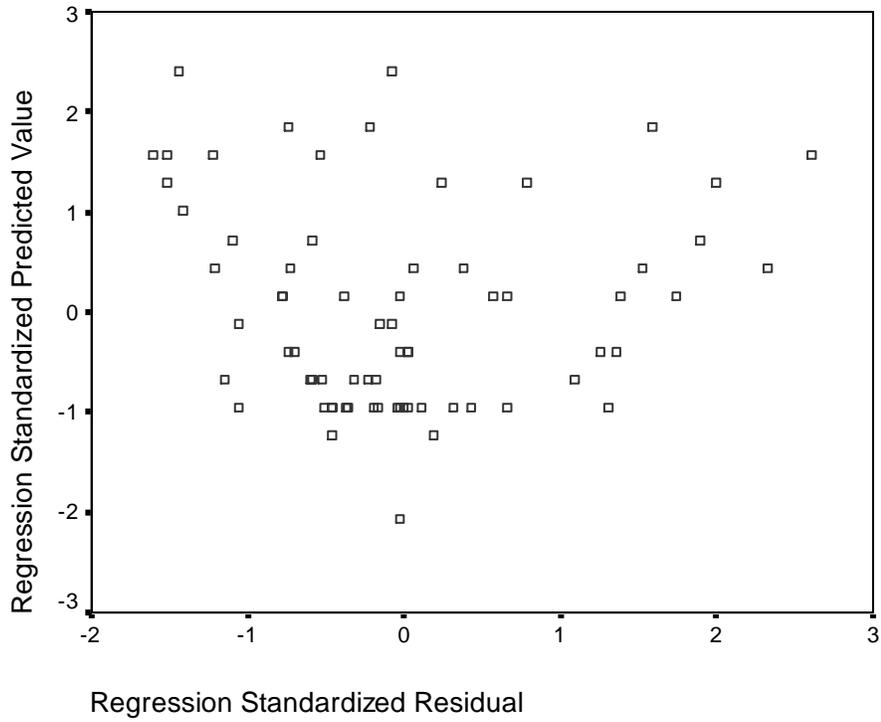
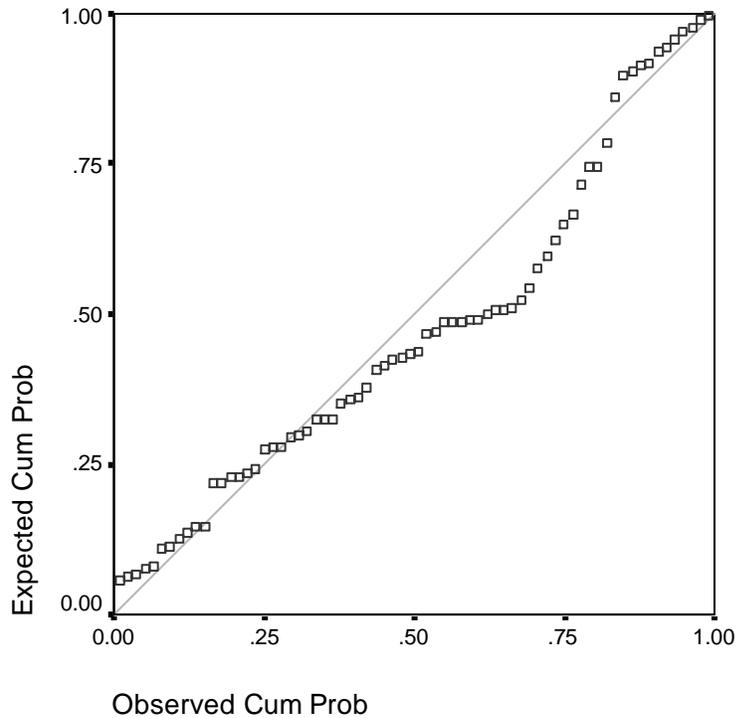


Figure 16. Scatterplot of residuals around regression line for dependent variable sustained attention satisfying homoscedasticity assumption



Satisfying the second criterion for mediation outlines by Baron and Kenny (1986), the null hypothesis was also rejected for this regression equation, $F(1,69) = 9.06, p < .01$. Hyperactive symptoms explained 12 percent of the variance in sustained attention ($\beta = -1.09, p < .01, \text{part} = -.343$). Based on a small effect size ($f^2 = .13$), the power for this analysis was 0.85.

The third and final step of the mediation procedure is regressing both hyperactive symptoms and sustained attention on the dependent variable short-term memory. Normality of errors (Figure 17), linearity (Figure 18), and homoscedasticity (Figure 19) were also satisfied for this regression.

Figure 17. Normal distribution of residuals satisfying normality of errors assumption for hyperactive symptoms and sustained attention regressed on short-term memory.

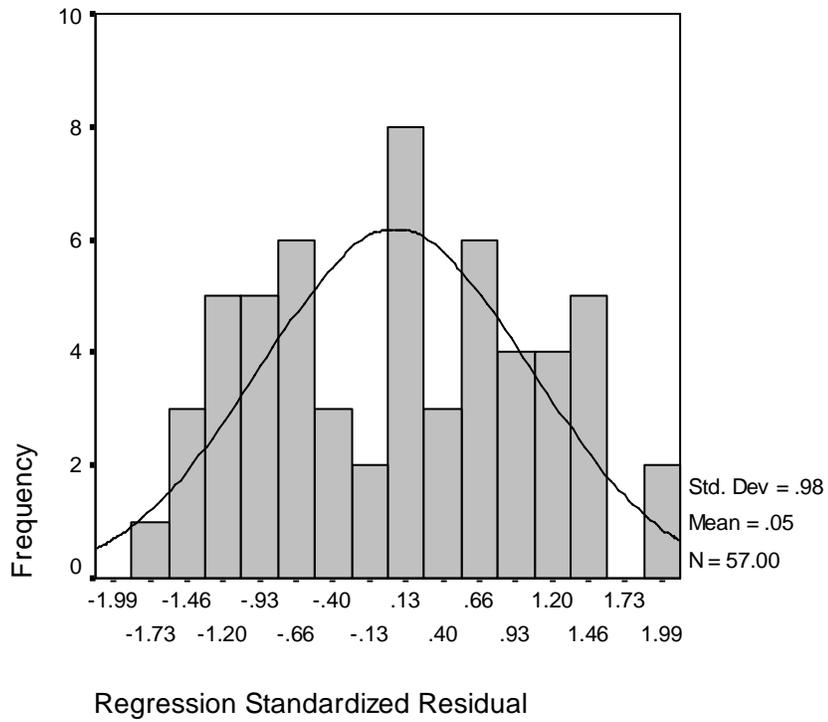


Figure 18. Scatterplot of standardized residuals showing satisfaction of linearity assumption for dependent variable short-term memory.

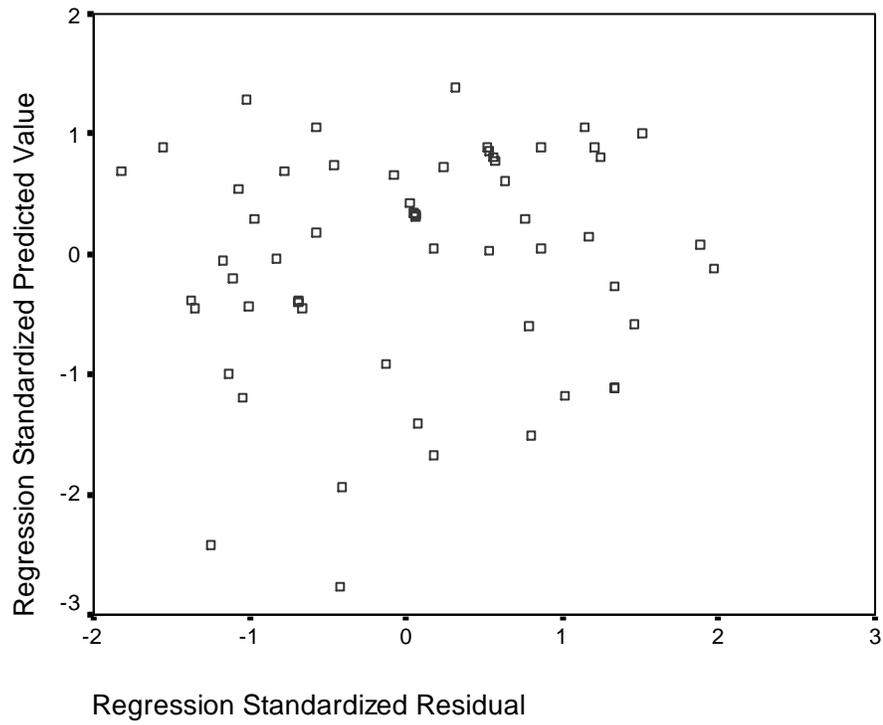
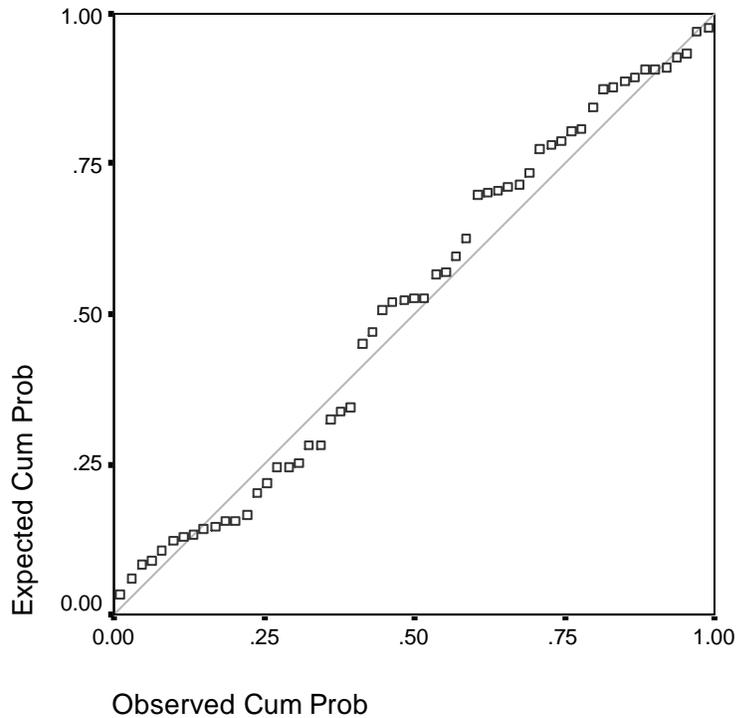


Figure 19. Scatterplot of residuals around regression line for dependent variable short-term memory satisfying homoscedasticity assumption



Inconsistent with the criteria outlined by Baron and Kenny (1986), the null hypothesis was also rejected for this equation, $F(2,59) = 4.84, p < .01$. Part correlations indicate that hyperactive symptoms contributed 5 percent unique variance ($\beta = .204, p = .07, \text{part} = .223$) and sustained attention contributed 5 percent unique variance ($\beta = -.06, p = .08, \text{part} = -.214$) to short-term memory. Based on a small effect size ($f^2 = 0.11$), the power for this analysis was 0.59.

Table 6

Regression analyses with sustained attention as a mediator between ADHD hyperactive symptoms and short-term memory.

	B	SE B	β	t	p
ADHD Hyperactive Regressed on Sustained					
ADHD Hyperactive	-1.09	0.36	-0.34	-3.01	0.004
ADHD Hyperactive Regressed on STM					
ADHD Hyperactive	0.27	0.11	0.32	2.53	0.01
ADHD Hyperactive and Sustained Regressed on STM					
ADHD Hyperactive	0.20	0.11	0.24	1.82	0.07
Sustained	-0.06	0.04	-0.23	-1.74	0.09

Note. SE = Standard Error; ADHD Hyperactive = Attention-Deficit/Hyperactivity

Disorder Hyperactive Symptoms; Sustained = Sustained Attention; STM = Short-term Memory

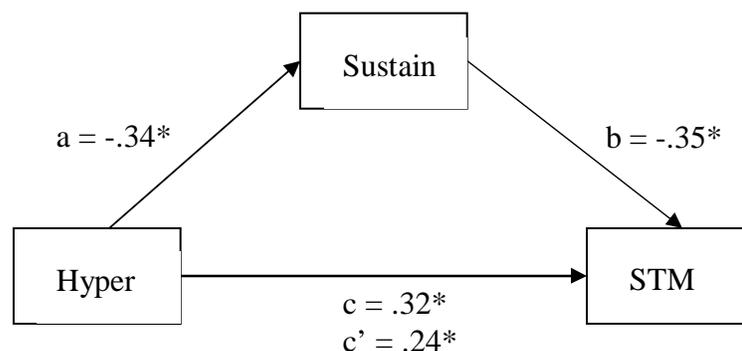
Baron and Kenny (1986) also recommend a direct significant test of the mediation (Sobel, 1982). The standard error of the indirect effect is calculated and converted to a z value, which is then tested for significance. Based on the Sobel (1982) method, the mediation effect of sustained attention between hyperactive symptoms and short-term memory is not significant ($z= 1.44, p=.15$).

There are limitations of the Baron and Kenny (1986) and Sobel (1982) approach to testing mediation. The Sobel (1982) procedure assumes normality of the standard error

distribution. Also, in the Baron and Kenny (1986) approach, there is a decrease in power for the third equation due to the expected multicollinearity between the independent variable and the mediation variable. In this case, the power decreased from 0.71 to 0.59 when the mediation variable was added to the model. This results in an over-estimation of the effect of the independent variable and an underestimation of the effect of the mediation variable. Bootstrapping the standard error is suggested for dealing with these power issues and compensating for non-normal standard error distributions (MacKinnon et al., 2002; Preacher & Hayes, 2004; Wu & Zumbo, 2007).

Bootstrapping was completed with 1,000 resamples and a 95 percent confidence interval for the standard error. Results of the bootstrap procedure indicate a lower limit of -.004 and an upper limit of .1820. As zero is included in the standard error distribution, the mediation effect of sustained attention is not significant; however, it appears that partial mediation is indicated.

Figure 20. Path diagram with sustained attention as mediation variable between ADHD hyperactive symptoms and short-term memory.



Note. * = standardized coefficients; Hyper = ADHD Hyperactive Symptoms; Sustain = Sustained Attention; STM = Short-term Memory; c' = Hyper and Sustain regressed on STM

Correction for Suppression Effects

Further examination of regression coefficients in comparison with bivariate correlation results indicates that a suppression effect occurred due to use of pairwise deletion for missing data. To correct for this effect, the regression analysis was re-run using listwise deletion for missing data. The results of this analysis are reported below in Table 7. As the four central executive variables all had the same sample size with this method, there was no need to split those variables into two equations. All four central executive variables were therefore included in model two.

Table 7

Regression analysis with listwise deletion and working memory as dependent variable

	B	SE B	β	t	p
<hr/> Model 1					
STM	0.33	0.2	0.27	1.67	0.1
<hr/> Model 2					
STM	0.13	0.2	0.1	0.63	0.09
Sustained	-.15	0.07	-.35	-2.07	0.05
Inhibition	0.05	0.06	0.13	0.82	0.42
Shifting	0.05	0.21	0.04	0.27	0.79
Retrieval	0.22	0.15	0.24	1.46	0.15

Note. SE = Standard Error; STM = Short-term Memory; Sustained = Sustained Attention; Inhibition = Selective Attention/Inhibition; Shifting = Shifting Attention; Retrieval = Control of Retrieval from Long-term Memory.

Results of this regression with short-term memory, sustained attention, inhibition, shifting, and retrieval regressed on working memory indicates again indicates that sustained attention contributes unique variance to working memory after including short-term memory. Short-term memory and all four central executive variables explained 25 percent of working memory variance ($R = .50$). Sustained attention was the only significant contributor to working memory variance in this equation. ($\beta = .10$, $p < .05$, $\text{part} = -.31$) and are consistent with the results of analyses utilizing pairwise deletion.

CHAPTER V

DISCUSSION

Summary of Working Memory Results

Based on the empirical working memory literature, it was hypothesized that four executive processes would contribute unique variance to total working memory variance after controlling for short-term memory variance. Contribution of unique variance by a construct to total working memory variance after controlling for short-term memory variance would indicate that a process is a component of the central executive. These four processes were hypothesized to be sustained attention, selective attention/inhibition, shifting attention, and control of retrieval from long-term memory.

Results of regression analyses indicate that after removing short-term memory variance, sustained attention contributes unique variance to working memory. This indicates that sustained attention is involved in the working memory at the executive level and should be included as a component of the central executive, pending replication of these results. Though Baddeley did not specifically implicate sustained attention as part of the working memory system, these results are consistent with Baddeley's suggestion that control of attention is part of the working memory system (Baddeley, 2002a, 2003). It is also consistent with Mirsky's (1991) model of attention which includes sustained attention as a component of the attention system and Posner and Raichle's (1994) assertion that a continuous alerting process is a component of attention. Swanson and colleagues (1998) then relate this continuous alerting process to sustained attention. These results, that sustained attention contributes unique variance to working memory, are also consistent with factor analytically derived models of attention showing

that sustained attention is a distinct type of attention (Manly et al., 2001; Robertson et al., 1996).

Selective attention/inhibition also contributed unique variance to working memory after controlling for short-term memory variance; however, this contribution was not statistically significant. This is inconsistent with the theoretically and empirically based models of central executive functioning and attention (Baddeley, 2003; Barkley, 1997; Mirsky et al., 1991; Posner & Raichle, 1994; Robertson et al., 1996), each of which contained a factor or process labeled selective attention or inhibition. One possible explanation for these results is that the shared variance between sustained attention and selective attention/inhibition was the same variance that was shared between selective attention/inhibition and working memory; however, after examining the preliminary bivariate correlations, this does not appear to be the appropriate explanation. Working memory and selective attention/inhibition did not correlate in that preliminary analysis. Rather, it appears that these results and the inconsistency with the available literature are related to differences between the sample utilized in this study and samples utilized in the previous research, i.e. a mixed clinic-referred sample as opposed to a pure ADHD or control sample. It may also be related to method variance as the measure utilized to measure inhibition was primarily visual and motor in terms of task demands whereas the measure for working memory was a verbal task. These differences in task demands may have attenuated the relationship between these two tasks.

Results of the second regression analysis with short-term memory, shifting attention, and control of retrieval from long-term memory regressed on working memory indicated that neither of these executive variables contributed unique variance to working

memory performance. The result that shifting attention did not contribute unique variance to working memory is inconsistent with Baddeley's (2002a) model of the central executive and results of central executive performance in Alzheimer's patients (Baddeley, 1996). It is also inconsistent with the model of the central executive hypothesized by Zoelch and colleagues (2005), with the neural-network based model of attention proposed by Posner and Raichle (1994), and with factor-analytically derived models of attention (Manly et al., 2001; Robertson et al., 1996). Based on the smaller sample size for this analysis and results of power analysis it appears that the small sample size may have prevented relationships between working memory and shifting attention and/or control of retrieval from being detected due to reduced power. Results of bivariate correlations appear to support this conclusion as control of retrieval from long-term memory correlated significantly with both working memory and short-term memory. Shifting attention, however, did not correlate with working memory or short-term memory, indicating that a type II error may not have occurred for this variable.

Working Memory Implications

Reflecting on the working memory literature, these results provide further support for the multicomponent models of working memory (Baddeley & Hitch, 1974; Baddeley, 2003; Cowan, 1999; Oberauer et al., 2003) and are in contrast with the unitary working memory models of Daneman and Carpenter (1980) and Engle and colleagues (Engle, 2002; Kane et al., 2004) in that both short-term memory and executive level tasks contributed variance to working memory performance. These results further support Baddeley's model of working memory (Baddeley & Hitch, 1974; Baddeley, 2003) in that short-term memory accounted for some, but not all of working memory. This is

consistent with the short-term memory processes, i.e. the phonological loop, included in Baddeley's model. Executive level processes, such as sustained attention, explained more of working memory than short-term memory alone, thus paralleling the slave system and central executive levels of Baddeley's working memory system.

The combination of short-term memory, sustained attention, and selective attention/inhibition accounted for 18 percent of working memory variance. These results indicate that a majority of working memory variance is not accounted for by the hypothesized central executive variables included in the current study. This indicates that the hypothesized central executive components in this study are not sufficient to explain all of the executive level variance of the working memory task used in this study. Further investigation is therefore needed to determine which executive processes comprise the central executive; however, the results of the current study appear to indicate that sustained attention is related to working memory and is a component of the central executive. Differences between Baddeley's hypothesized central executive components and results of the current study may be due to Baddeley's research focusing on geriatric patients with Alzheimer's Disease (Baddeley, 1996, 2002a); whereas the current sample was clinic-referred children. This may indicate that executive processes in the working memory system are not consistent across clinical groups and/or across the lifespan.

The relationship between the working memory system and long-term memory hypothesized by Baddeley (2002a, 2003) through the central executive and episodic buffer was not supported by the current study in that the variable control of retrieval from long-term memory was not related to performance on this working memory task; however, the control of retrieval from long-term memory variable was correlated with

both working memory and short-term memory in preliminary analyses. This further suggests that insufficient power may have resulted in a type II error for this variable. This is consistent with reports by Mirsky and colleagues (1991) that the factor labeled encoding in their model, which is described as recall and manipulation of information, was not found consistently across factor analyses of attention measures. Control of retrieval from long-term memory was considered an exploratory variable in the current analysis as its inclusion in models of attention and working memory is primarily theoretical at this time (Baddeley, 2000; 2002a; 2003). This study was the first to attempt to empirically validate this relationship. As lack of sufficient power may have masked these results, further investigation of this relationship is also needed.

Results of the current study also support results of meta-analysis completed by Martinussen and colleagues (2005). They found moderate effect sizes for both working memory and short-term memory tasks between controls and children with ADHD indicating that WM difficulties for children in clinical populations may result from STM and WM processes, consistent with the relationships founding the current regression analyses. Results of this study are also consistent with Kail and Hall's (2001) discussion of working memory defined as short-term memory plus additional attentional resources required to complete complex tasks. This parallels the regression results that short-term memory and additional attention processes, in this case sustained attention, contribute unique variance to working memory.

In addition to paralleling the results of Martinussen and colleagues (2005) and Kail and Hall (2001), these results are also consistent with results of structural equation modeling completed by Alloway and colleagues (2004). In a child sample, Alloway and

colleagues (2004) showing multiple factors in working memory including the phonological loop and central executive. Current study results were not consistent with the Alloway and colleagues (2004) factor labeled the episodic buffer as the current results do not appear to support this link with long-term memory. The other factors found by Alloway and colleagues (2004) may provide some explanation of the working memory variance not accounted for in the current study's results. They found that phonological awareness and nonverbal ability also contributed variance to their working memory tasks in addition to the central executive, phonological loop, and episodic buffer. Though Alloway and colleagues (2004) utilized an experimental working memory task different from the letter-number sequencing task, it suggests that related task demands may account for some of the unexplained variance in the current study.

In summary, based on results of the current study, sustained attention appears to be a key component of the central executive based on the unique variance it contributes to working memory even after removing short-term memory variance. Sustained attention should be considered as a potential related difficulty in children demonstrating working memory difficulties. Further investigation is also warranted to continue to investigate what executive processes are related to working memory. Control of retrieval from long-term memory in particular should be investigated further as lack of power may have resulted in a type II error for this variable that demonstrated a significant correlation with both working memory and short-term memory in Pearson correlational analyses.

Summary of ADHD Symptom Results

Based on the extant literature showing consistent deficits in working memory in the ADHD population (e.g. Cornoldi et al., 2001; Fuggetta, 2006; Karatekin, 2004) and

evidence of correlations between symptoms of ADHD and performance on executive tasks (Muir-Broddas et al., 2002; Sonuga-Barke et al., 2002), it was hypothesized that ADHD inattentive symptoms would explain variance in working memory performance and that hyperactive and impulsive ADHD symptoms would not explain additional variance in working memory performance after inclusion of inattentive symptoms.

In contrast with hypothesized relationships, examination of bivariate correlations in the current study indicated that ADHD inattentive, hyperactive, and impulsive symptoms did not correlate with working memory performance. There was also a strong correlation among the ADHD symptom domains, indicating that there is a great deal of similarity among these symptom domains. These results support the conclusions of Wilcutt and colleagues (2005) that showed no differences in effect size among ADHD subtypes on measures of executive functioning in meta-analysis. These results showed no difference in relationships between subtypes of ADHD and performance on various executive measures. As Wilcutt and colleagues (2005) looked at diagnostic categories rather than domains of symptoms it is possible that the similarities in effect size across subtypes of ADHD are a reflection of the shared variance in symptoms across diagnostic subtypes. In the current study, this shared variance among the symptoms domains made it impossible to examine them independently in further analyses. For this reason all further analyses included only hyperactive symptoms as representative of the ADHD symptom domains.

The result that ADHD symptoms did not correlate with working memory performance is consistent with Sonuga-Barke and colleagues (2002) who found that inattentive symptoms of ADHD did not correlate with working memory performance in a

preschool sample. These results are, however, inconsistent with most of the literature in this area. These results are inconsistent with Barkley's (1997) model of ADHD which links executive dysfunction associated with symptoms of ADHD with working memory dysfunction. These results are also inconsistent with Chhabildas and colleagues (2001) who found that ADHD inattentive symptoms were predictive of measures of inhibition, vigilance, and processing speed. The results for hyperactive and inattentive symptoms are, however, consistent with Chhabildas and colleagues (2001) finding that ADHD hyperactive and impulsive symptoms were not predictive of inhibition, processing speed, and vigilance measures.

Implications for ADHD Symptoms

The result that no domain of ADHD symptoms was related to working memory performance is inconsistent with Barkley's model (1997). In Barkley's (1997) model of executive processing in ADHD, inhibition deficits lead to downstream deficits in working memory. In the current study, ADHD symptoms were related to short-term memory, one component of working memory, but were not related to overall working memory performance. Performance on the inhibition task was also not related to working memory. Both of these results are inconsistent with Barkley's model. It should be noted, however, that Barkley's model was originally based on the ADHD population (1997) and later generalized to apply to control of behavior in a variety of clinical populations (Barkley, 2000) whereas the current study examined ADHD symptoms in a clinical population including but not limited to children with ADHD which may limit the application of Barkley's model to results of this study. Also, in contrast with Barkley's model, inhibition was not related to working memory performance in this study. This may

indicate that Barkley's model does not adequately explain working memory dysfunction. It may also be related to method variance as the measure utilized to measure inhibition was primarily visual and motor in terms of task demands whereas the measure for working memory was a verbal task. These differences in task demands may have attenuated the relationship between these two tasks.

The result that ADHD symptoms are not related to working memory is also inconsistent with the Nigg and Casey (2005) model. Nigg and Casey (2005) suggested that difficulties with inhibition and set shifting combine to cause downstream difficulties with working memory in children with ADHD. In the current study, neither set shifting nor inhibition contributed significant variance to working memory. This may indicate that the Nigg and Casey model may also not be sufficient to explain working memory dysfunction and its relationship with ADHD symptoms. The results of the current study are, however, consistent with the Nigg and Casey (2005) model of executive dysfunction in one respect. In the current study, one executive process is not sufficient to explain all of the variance in working memory performance. This is consistent with Nigg and Casey's (2005) proposal that executive dysfunction, including working memory, is the result of a combination of processes functioning together. In this case the identified processes are short-term memory and sustained attention. The fact that these two variables only explained 18 percent of working memory variance also appears to indicate that other processes are involved in completion of working memory tasks, consistent with the suggested complexity of executive dysfunction (Nigg & Casey, 2005).

In this sample, ADHD symptoms were related to short-term memory performance. This is consistent with some working memory studies (Kalff et al., 2002;

Loge, Stanton & Beatty, 1990); however, it is inconsistent with most studies indicating that children with ADHD perform as well as controls on short-term memory tasks and are deficient on working memory tasks (e.g. Karatekin, 2004; McInnes et al., 2003). As short-term memory is a component of total working memory functioning, it is appropriate to further examine the relationship between ADHD symptoms, short-term memory, and central executive processes.

Summary of Mediation Analysis Results

Based on previous literature findings, it was hypothesized that central executive components of working memory would mediate the relationship between symptoms of ADHD and working memory performance. In the current sample, none of the ADHD symptom domains correlated with working memory performance. A relationship was evident however between all domains of ADHD symptoms and the short-term memory level of working memory based on bivariate correlation results. Results of multiple regression with sustained attention and selective attention/inhibition as predictors of short-term memory also showed that sustained attention contributed unique variance to the short-term memory level of working memory in addition to working memory as a whole. It should be noted that sustained attention contributed less variance to short-term memory (12 percent) than to working memory (17 percent). This makes sense empirically and theoretically as short-term memory is a lower-level process of the complex working memory system.

As previously noted, because of the high intercorrelations among ADHD symptom domains, mediation analyses were completed with only one ADHD symptom domain, hyperactive symptoms. Based on the criteria established by Baron and Kenny

(1986), two of three criteria were satisfied for full mediation by sustained attention between ADHD hyperactive symptoms and short-term memory performance. The first criterion required that hyperactive symptoms contribute significant variance to short-term memory. This criterion was satisfied as hyperactive symptoms explained 10 percent of short-term memory variance. This is consistent with previous research (Muir-Broddas et al., 2002). The second criterion was also satisfied with hyperactive symptoms accounting for 12 percent of the variance in sustained attention. This relationship between ADHD symptoms and sustained attention is consistent with previous studies finding sustained attention deficits in children with ADHD relative to controls (Heaton et al., 2001; Kearns, McInerney, & Wilde, 2001; Manly et al., 2001; Shallice et al., 2002). The third criterion for mediation was that hyperactive symptoms would no longer contribute unique variance to short-term memory after sustained attention was added to the model. After sustained attention was added to the model, the amount of variance contributed to short-term memory by hyperactive symptoms was reduced from 10 percent to 5 percent. Based on the Baron and Kenny (1986) criteria, sustained attention is not a complete mediator of the relationship between hyperactive symptoms and short-term memory. The direct test of the mediation for significance (Sobel, 1982) and the bootstrapping procedure used to correct for non-normality in the standard error distribution (MacKinnon et al., 2002; Preacher & Hayes, 2004; Shrout & Bolger, 2002; Wu & Zumbo, 2007) indicated that the mediation effect is not significant. Because directional hypotheses were used in this mediation model, it is possible that the lower bound of the bootstrapped confidence interval may be too conservative. Had a less conservative boundary been utilized, the mediation effect may have met criteria for statistical significance. Though not a full

mediation, the decrease in relationship between hyperactive symptoms and short-term memory after sustained attention is added appears to indicate some partial mediation. These results indicate that the central executive process sustained attention does explain some of the relationship between ADHD symptoms and short-term memory performance.

As previously noted, in mediation analyses, the relationship between the independent variable and dependent variable is often overestimated; whereas the mediation relationship is typically underestimated due to expected multicollinearity in the mediation equation. This makes it more difficult to find a significant mediator. Based on this information, the mediation effect of sustained attention is most likely an underestimate of the true mediation effect.

Implications of Mediation Analysis

Given that the central executive is proposed to have a top-down effect on the slave systems tapped by short-term memory tasks (Baddeley, 2003), it may be that in the current study, executive variance is also captured by the short-term memory task. After removal of this short-term memory variance, it then appears that a majority of the executive processes are not related to overall working memory. This may explain why sustained attention, as a component of the central executive, would potentially have a partial mediation effect between ADHD symptoms and short-term memory performance. The potential mediation identified in this study is consistent with Baddeley's model in that sustained attention, as a component of the central executive, would have top-down influence over short-term memory (Baddeley, 2003).

These results in conjunction with past research (Karatekin, 2004; McInnes et al., 2003) appear to indicate that ADHD symptoms impact working memory at both the

short-term memory and executive levels. Had a full mediation been found, the implication would be that ADHD symptoms were impacting working memory solely through sustained attention at the executive level. As only a partial mediation was indicated, it appears the ADHD symptoms may have a direct effect on short-term memory and an indirect effect on short-term memory through executive processes such as sustained attention. Based on these results, it is also possible that ADHD symptoms may have a bottom-up effect, affecting working memory through the short-term memory process rather than having a top-down effect through the executive processes as previously thought (Barkley, 1997; Nigg & Casey, 2005). If the short-term memory process is disrupted by ADHD symptoms and information is not properly processed and retained in the phonological loop, then higher-level tasks may be disrupted.

Summary of Results

Overall, results of this study indicate that sustained attention is an executive process that contributes unique variance to working memory even after controlling for short-term memory variance. This appears to support sustained attention as a component process of the central executive. If a child is demonstrating difficulties in working memory, sustained attention should also be evaluated to determine if difficulties with sustained attention are contributing to difficulties with working memory. Further investigation with a larger sample size is needed to evaluate other executive processes as potential central executive processes in the working memory system.

In the current study, ADHD symptoms were not related to working memory performance. They were, however, related to short-term memory performance. This result indicates that the effect of ADHD symptoms on working memory system may not

be limited to the executive level. Rather, symptoms of ADHD may also have an effect at the short-term memory level.

In terms of the mediation, it appears that sustained attention difficulties account for part of the relationship between ADHD symptoms and short-term memory performance. This appears further support that ADHD symptoms have an impact on working memory at both the short-term memory level and at the executive level through sustained attention.

Limitations

The current study sought to improve on several issues in the existing research. First, all measures used in the current study are established as reliable and valid measures of the constructs they were purported to assess. Second, symptoms of ADHD were utilized as a continuous variable rather than implementing arbitrary cut scores for diagnostic categories. Despite these improvements to the research methodology of this area of study, several limitations remain for the current study. The primary limitations of the current study are based in the sample. First, sample size was too small to utilize structural equation modeling, the most parsimonious approach for answering these research questions. As a result, constructs were represented by one score rather than by latent variables. Executive functions measures typically do not measure one cognitive process, resulting in extraneous variance. Use of single measures for each score does not address this error in scores as use of latent variables would have. Though efforts were made to triangulate scores to isolate processes, it cannot be determined with certainty that the variables utilized were tapping isolated executive processes. This error variance may have affected the analyses.

The sample characteristics were also a hindrance in the multiple regression analyses. The sample size for shifting attention and control of retrieval from long-term memory was also too small, because of missing data, to have all central executive variables as predictors in the same equation. When the regression was completed with these two variables as predictors, the power was too low to detect shared variance between them and working memory.

Another limitation related to the study sample is the use of a clinic-referred sample rather than an ADHD diagnosis sample or control sample. Though there were benefits to utilization of this mixed sample, i.e. larger total sample size and normal distribution of ADHD symptoms rather than having a restricted range for these variables, this mixed sample may have introduced more error variance into the analyses. Symptoms of ADHD, particularly attention difficulties, are a symptom of a number of disorders including anxiety and depression (American Psychiatric Association, 2000). Though children with other diagnoses may have similar symptoms to ADHD, the etiology of these symptoms and relationships between these symptoms and executive functions may be different than those of children with ADHD. These differences then become error variance in the equations.

In this sample, the medication status, i.e. medicated or non-medicated, of each participant at the time of data collection was unknown. Effect of medication on executive functions performance was inconsistent in the literature (Barkley et al., 2001; Barnett et al., 2001; Bedard, Martinussen, Ickowicz, & Tannock, 2004; Heaton et al., 2001; Kempton et al., 1999; Tannock, Ickowicz, & Schachar, 1995). The impact of medications on these children's performance could therefore not have been predicted based on

previous literature and is extraneous variance. Though children in the sample may have been taking medication at the time of the assessment, they demonstrated behaviors sufficient to warrant a clinical evaluation. The impact of any child's specific medication status on these behavioral presentations cannot, however, be determined. Future studies may strive to control for this unexplained variance by testing children when they are not medicated, conducting preliminary analyses to determine medication effects on study variables, or covarying for medication effects in the analyses.

One final limitation of the current study is that the working memory measure selected is a verbal task. As a result, the visuo-spatial sketchpad was not assessed in the current study. Results can therefore only be generalized to verbal working memory performance.

Recommendations

In future studies, it is recommended that replication of the current study occur in both control samples and in specific clinical population including an ADHD sample to examine if working memory functions are consistent across diagnostic groups. Replication with both visuospatial and verbal working memory measures is also recommended to gain further understanding of interrelationships among all working memory processes. It is also recommended that the interrelationships among ADHD symptoms, short-term memory, and working memory be further investigated including potential mediation and moderation relationships with sustained attention and other executive processes.

It is also recommended that larger sample sizes be utilized in future working memory research to facilitate more parsimonious analyses such as structural equation

modeling and use of latent variables to reduce extraneous variance in studies examining executive functions constructs. Relatedly, further investigation is needed to establish construct validity of currently used executive functions and working memory measures.

As it has been previously established that children's working memory can be improved through intervention (Klingberg et al., 2005; Klingberg, Forssberg, & Westerberg, 2002), the results of the current study should be linked to empirical interventions for working memory. Potential studies would include an examination of the impact of improving sustained attention on working memory performance and examining changes in academic performance related to improvement of working memory. Empirical linkages also need to be established between results of working memory assessments and appropriate interventions to improve this area of cognitive functioning.

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