# MODERATORS OF SHORT-TERM AND WORKING MEMORY DEFICITS IN CHILDREN WITH ATTENTION-DEFICIT/HYPERACTIVITY DISORDER (ADHD): A META-ANALYTIC REVIEW

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# MODERATORS OF SHORT-TERM AND WORKING MEMORY DEFICITS IN CHILDREN WITH ATTENTION-DEFICIT/HYPERACTIVITY DISORDER (ADHD): A META-ANALYTIC REVIEW

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# CHAPTER I

## INTRODUCTION

Attention-Deficit/Hyperactivity Disorder (ADHD) is a pervasive childhood disorder that affects approximately 3 to 7% of the population (Ek et al., 2007; Polanczyk & Luis, 2007) and is characterized by difficulties with hyperactivity, impulsivity, and sustained attention (Barkley, 2006). Presence of the disorder conveys increased risk for several pejorative outcomes including long-term scholastic underachievement (e.g., lower GPA, SAT, and ACT scores, and a higher rate of failure in college) and interpersonal relationship and peer problems (e.g., more marital problems and higher divorce rates) in affected individuals, long-term impairments across more major life activities than most other disorders seen in outpatient mental health clinics, and an estimated annual societal cost that ranges between $36 billion and 52.4 billion (Pelham, Foster, & Robb, 2007).

Working memory has garnered particular attention as a potential core deficit or endophenotype of ADHD (Rapport et al., 2008). The term *endophenotype* refers to a feature of a disorder that underlies clinical symptoms (i.e., phenotypic expression of the disorder), is less genetically complex, and is closer to the genome relative to the disorder's phenotype. Working memory is responsible for producing and maintaining cognitive representations of stimuli, searching for same or similar stimuli in memory, and grasping and maintaining appropriate behavioral responses for a given stimuli. The working memory system is comprised of a central executive and two subsidiary components – the phonological and visuospatial storage/rehearsal subsystems (Baddeley, 2007). The central executive (CE) is an attentional controller responsible for oversight and coordination of the subsidiary systems. Its primary functions are focusing attention, and dividing attention among concurrent tasks. The phonological (PH) subsystem is responsible for the temporary storage and rehearsal of verbal material, whereas the visuospatial (VS) subsystem provides this function for non-verbal visual and spatial information.

In contrast to prevailing models of ADHD that do not consider working memory (Sergeant, 2005) or suggest working memory deficits occur secondary to disinhibition (Barkley, 1997; Sonuga-Barke, 2003), Rapport's model of ADHD hypothesizes that working memory is a central core component of the disorder that is upstream of phenotypic features such as inattention, hyperactivity, and impulsivity (Rapport, Chung, Shore, & Isaacs, 2001). A recent meta-analytic review as well as experimental studies indicate that children with ADHD are impaired in all three components of working memory, with the largest deficits found in the domain-general central executive system, followed by visuospatial storage/rehearsal and then phonological storage/rehearsal subsystems (i.e., deficits in CE > VS > PH; Marzocchi et al., 2008; Rapport et al., 2008; Martinussen, Hayden, Hogg-Johnson, & Tannock, 2005; Willcutt et al., 2005). The validity of working memory as a core deficit, however, has been challenged by recent studies that fail to uniformly find working memory deficits in affected children with the disorder (Tannock, 2009).

The current study sought to update the previous meta-analytic review with the inclusion of new studies. Meta-analytic techniques were employed to examine the effects of previously unexamined moderator variables such as Percent Female, Age, Diagnostic Method, Trials per Set Size, Performance Metric, Response Modality, Simple Manipulation, and CE Demand. First, effect size estimates and homogeneity analyses were performed. Potential moderator effects were explored after the homogeneity assumption was rejected. A fixed-effects weighted regression approach was used to provide a measure of overall fit ($Q_R$), as well as an error/residual term ($Q_E$). A significant $Q_R$ indicates that the model accounts for significant variability among effect sizes. A corrected B-weight standard error for each moderator was tested against the z-distribution (Lipsey & Wilson, 2001). The standard error of the beta-weight was divided by the square root of the mean square of the residual, and then the beta-weight was divided by the corrected standard error of the beta-weight. This z-value was compared to a z-table to determine if the moderator was statistically significant (Lipsey & Wilson). An overall table of effect sizes and moderating variables is reported (Table 1) as well as a table for the weighted regression analysis (Table 2).

# CHAPTER II

## REVIEW OF LITERATURE

### Overview of Attention-deficit/Hyperactivity Disorder (ADHD)

Attention-Deficit/Hyperactivity Disorder (ADHD) is a pervasive childhood disorder that affects approximately 3% to 7% of the population (Ek et al., 2007; Lee, Oakland, Jackson, & Glutting, 2008; Polanczyk et al., 2007; Weyandt & DuPaul, 2006) and is characterized by difficulties with hyperactivity, impulsivity, and sustained attention (Barnett et al., 2001). The DSM-IV (American Psychological Association, 2000) provides additional diagnostic nomenclature that distinguishes three subtypes including Predominantly Inattentive (ADHD-I), Predominantly Hyperactive-Impulsive (ADHD-H/I), and Combined (ADHD-C). The Predominantly Inattentive subtype of ADHD is characterized by frequent careless mistakes in schoolwork, difficulty organizing tasks, and forgetfulness in daily activities. Children with ADHD-I experience difficulty sustaining attention and following directions and are easily distracted by irrelevant stimuli, whereas symptoms associated with ADHD-H/I are characterized by frequent fidgeting/restlessness, excessive talking, and/or difficulty taking turns and staying seated (Bauermeister et al., 2005). Children receive an ADHD-C diagnosis when at least six symptoms of both inattention and hyperactivity-impulsivity are present.

Recent estimates suggest prevalence rates of 3% for ADHD-I, 2% for ADHD-HI, and 5% for ADHD-C in the general population (community sample), and 78% for ADHD-I, 53% for ADHD-HI, and 93% for ADHD-C in clinical samples (Lee et al., 2008; Rowland et al., 2008). Recent epidemiological studies suggest these base rates are moderated by demographic variables such as gender, ethnicity, and diagnostic methods. For example, males are more commonly diagnosed than females, with ratios ranging from 2:1 for the Inattentive subtype to 9:1 for the Combined subtype (Froehlich, 2007; Lee, Oakland, Jackson, & Glutting, 2008), and African-American children are more frequently diagnosed relative to Caucasian children (Costello & Janiszewski, 1990; Jarvinen & Sprague, 1995; Reid et al., 2000). Increased risk of prenatal factors such as exposure to toxins is associated with higher rates in the African-American population relative to Caucasians (Reid et al.; Samuel et al., 1999). Conversely, western-biased assessment instruments that are not culturally sensitive may underestimate prevalence rates in African-Americans (Anderson, 1996; Barkley, 1998; Bird, 2002). Diagnostic procedures that rely solely on affected children's self-report of symptoms are associated with lower prevalence rates (7%) relative to estimates derived from more comprehensive methods (11%) that include collateral informants (e.g., parents and teachers; Fischer, 1997). Finally, base rates of ADHD in clinic-referred samples (6:1) are approximately twice as large as those obtained from community samples (3.4:1; Garland et al., 2001; Wolraich, Hannah, Pinnock, Baumgaertel, & Brown, 1996).

Conflicting prevalence rates may also result from reification errors and construct confusion. For example, although the constructs hyperactivity and impulsivity load on a single dimension in factor analytic studies (Hinshaw, 1992), *gold standard* assessment measures such as semi-structured interviews and standardized ratings scales frequently treat hyperactivity and impulsivity as discrete variables (Pasini et al., 2007). *Hyperactivity* refers to observable, kinetic activity that is not necessarily present in all children with attention deficit diagnoses (Hinshaw, 1987) while the term *impulsivity* is often used to label both observable phenomena (i.e., an impulsive overt action), and/or internal processes (e.g., non-reflective decision making; Barkley et al., 2001; Sonuga-Barke et al., 2010). Lack of construct differentiation may be due to multiple factors including imprecise definitions (Barkley et al.; Willcutt et al., 2001), construction of scale items from one diagnostic criteria (American Psychological Association, 2000), and an expected degree of shared variance (i.e., acting impulsively frequently necessitates motor activity; Rapport et al., 2008). Rater confusion also contributes to difficulty with diagnostic classification. For example, direct observations (McGrath et al., 2004) and actigraphs (Bauermeister et al., 2005) reliably detect changes in gross motor activity, whereas impulsivity is typically inferred as an explanation or cause of observed behavior.

The Predominantly Inattentive subtype of ADHD is markedly distinct from the Hyperactive/Impulsive subtype. Children diagnosed with ADHD-I are more likely to exhibit signs of boredom during tasks, self-consciousness, and lack of motivation (Bauermeister et al., 2005). A “sluggish cognitive tempo”, or lethargic, passive cognitive style has been suggested as a cause for such behaviors (Adams, Derefinko, Milich, & Fillmore, 2008; Bauermeister et al.). ADHD-Inattentive type is typically associated with a later age of onset, later age of referral, and occurs more frequently in females compared to ADHD-Combined type (Adams, Derefinko, Milich, & Fillmore; Baumeister et al.; Harrington & Waldman). ADHD-I is also associated with a unique genetic profile and a distinct pattern of transmission to subsequent generations (usually passed down through females) in comparison to ADHD-C (Adams, Derefinko, Milich, & Fillmore).

Presence of ADHD conveys increased risk for several pejorative outcomes including long-term scholastic underachievement and interpersonal peer problems (for reviews, see Barkley, Fischer, Smallish, & Fletcher, 2006; Mannuzza, Klein, Bessler, Malloy, & LaPadula, 1993). Previous research has reported long-term impairments across more major life activities than most other disorders seen in outpatient mental health clinics (Barkley, Murphy, & Fischer, 2008), and an estimated annual societal cost that ranges between $36 billion and $52.4 billion (Pelham, Foster, & Robb, 2007). Academic impairments such as difficulty completing schoolwork/homework, staying in one's seat, paying attention in class, and blurting out answers are the most common reason for referral for children with ADHD (McInnes et al., 2003). Children with ADHD frequently struggle with peer interactions due to poor insight and low self-monitoring (Shue & Douglas, 1992; Wiers, Gunning, & Sergeant, 1998), and disruptive behavior such as impulsivity, failing to wait their turn, and interrupting conversations (Knouse et al., 2008). Underdeveloped interpersonal skills such as persistent questioning may lead to increased frustration among peers, difficulty making friends (Knouse, et al.; Landgraf, 2007; Reaser, Prevatt, Petscher, & Proctor, 2007; Young, Toone, & Tyson, 2002), greater likelihood of bullying or being bullied (Bagwell et al., 2001), and greater loneliness (Heiman, 2005). Parent ratings suggest that children with ADHD exhibit more anger compared to controls, express anger in socially inappropriate ways, are less comfortable in assertive situations, have poorer parent-child relationships, and experience an overall lower quality of life (Weyandt & DuPaul, 2006). ADHD-I has high co-morbidity rates with internalizing (i.e. anxiety) disorders, and lower co-morbidity rates with externalizing disorders (Conduct Disorder, Oppositional Defiant Disorder), while the reverse is true for ADHD-C (Adams, Derefinko, Milich, & Fillmore; Bauermeister et al., 2005).

## Core Deficits and Endophenotypes of ADHD

Within the last several years, there has been increased interest in the identification of potential endophenotypes of Attention-Deficit/Hyperactivity Disorder (Castellanos & Tannock, 2002; Crosbie, Pérusse, Barr, & Schachar, 2008). The term *endophenotype* refers to a feature of a disorder that underlies clinical symptoms (i.e., phenotypic expression of the disorder), is less genetically complex, and is closer to the genome relative to the disorder's phenotype. Whereas a phenotype may reflect the complex interaction of a child's genotype, epigenetic factors, and environmental influences, endophenotypes provide an intermediate link between clinical symptoms (e.g., hyperactive and inattentive behavior) and a fewer number of genes (Gottesman & Gould, 2003). The endophenotypic approach is advantageous to the examination of ADHD because it holds considerable promise for the eventual development of more objective neurocognitive diagnostic procedures with improved predictive power relative to current best practices (Crosbie et al., 2008). Investigation of candidate endophenotypes also provides information about the directional relationship between clinical traits and consequently more accurate identification of a disorder's core features (Gottesman & Gould, 2003).

Because a disorder's phenotype is more susceptible to epigenetic and environmental factors relative to endophenotypes (Gottesman & Gould, 2003; Mill & Petronis, 2008), long-term treatment gains are less likely when phenotypes are the target of interventions (Rapport, Chung, Shore, & Isaacs, 2001). Findings from controlled, multi-site near-, intermediate- and long-term (Jensen et al., 2007; Molina et al., 2009) studies uniformly reveal that current treatments for ADHD are at best maintenance therapies, whose large magnitude but short-term benefits rapidly wane once active treatment components (i.e., pharmacological or behavioral) are removed. These findings imply that current treatments target the disorder's phenotypic expression rather than core deficits (Rapport et al., 2001). Interventions that effectively improve identified underlying endophenotypes, in contrast, are likely to positively affect secondary, behavioral symptoms of the disorder (i.e., inattentive, hyperactive, and impulsive behavior), and once developed hold considerable promise for promoting long-term treatment gains. Consequently, effective treatment and prevention of ADHD is dependent upon a comprehensive understanding of its underlying mechanisms and core, endophenotypic features.

Working memory has gained particular interest in recent years as a potential endophenotype or core deficit of ADHD (Castellanos & Tannock, 2002; Crosbie et al., 2008). However, while some models hypothesize working memory is a core deficit (Rapport et al., 2001; Rapport, et al., 2008) or an endophenotype (Castellanos & Tannock, 2002), others suggest working memory deficits occur downstream from deficient inhibitory processes (Barkley, 1997; Sonuga-Barke, 2002). Consequently, the central role of working memory in the expression of the ADHD phenotype continues to garner debate (Alderson et al., 2010; Schachar et al., 2001; Rucklidge & Tannock, 2002). A review of Baddeley's working memory model and the role of working memory in current models of ADHD is provided below.

# Baddeley's Working Memory Model

## Overview

Working memory refers to the active process of storing and manipulating internal information (Baddeley, 2003). Baddeley's working memory model is comprised of a domain-general, central executive controller and two subsidiary systems, the phonological loop and visuospatial sketchpad, that allow for the temporary storage and rehearsal of phonological (auditory or text) and visual information, respectively.

## Phonological Loop

The phonological (PH) loop contains two parts: a buffer that provides temporary storage of phonological information, and an articulatory rehearsal component that maintains information in the buffer. In the absence of rehearsal, the buffer is capable of storing information for approximately two seconds before it begins to decay (Baddeley & Hitch, 1974; Jacquemot, Dupoux, Decouche, & Bachoud-Levi, 2006). Evidence for the phonological loop is provided by the *phonological similarity effect*. Stimuli that sound similar (e.g., cat, hat) are less likely to be recalled accurately relative to a string of stimuli that sound different (e.g., car, pencil), suggesting that similar sounding words interfere with each other during the subvocal rehearsal process (Acheson, Postle, & MacDonald, 2010; Baddeley, 1966; Conrad & Hull, 1964). Alternately, recall of similar meaning words (e.g., car, automobile), a process involving access to long-term memory, has little to no effect on immediate word recall (Baddeley, 1966; Taft & van Graan, 1998). Evidence for the articulatory rehearsal component of the phonological loop is provided by studies of the *word length effect*. Strings of words are more likely to be recalled when each word is relatively short because shorter words can be rehearsed more frequently than longer words when total rehearsal time is held constant (Baddeley, Thomson, & Buchanan, 1975; Bhatarah, Ward, Smith, & Hayes, 2009). Additional evidence of articulatory rehearsal is provided by dual task studies that require participants to repeat a word such as *the* or *la* following the presentation of a list of words. Participants' word recall accuracy during the dual-task procedure is worse relative to performance during simple recall tasks because repetition of the word *the* or *la* interferes with articulatory rehearsal of the word list (Hanley & Bakopoulou, 2003).

### Visuospatial Sketchpad

The visuospatial (VS) sketchpad processes visual and spatial information in much the same way that the phonological loop processes auditory information. The system, independent of the phonological loop (Baddeley, 1966; Jacquemot, Dupoux, Decouche, & Bachoud-Levi, 2006), is responsible for temporarily storing and manipulating visuospatial information from incoming stimuli or retrieved from long-term memory (Baddeley, 2007). Evidence for the visual/object portion of the system is often provided by studies that examine performance on a pattern span task in which participants are required to recall or recognize a pattern of shaded cells in a visual matrix after a brief interval of time (Della Sala, Gray, Baddeley, Allamano, &Wilson, 1999). Alternately, the Corsi block task, in which subjects must repeat a string of tapping movements on blocks previously tapped by the researcher, is often used to examine the spatial component of the sketchpad (Della Sala, Gray, Baddeley, Allamano, &Wilson). Subjects learn a series of tapping movements by spatially encoding the pattern into working memory. A previous study examined the performance of brain-damaged patients and healthy normal controls on the pattern span and Corsi block task. Results indicated that visual interference significantly reduced visual but not spatial performance, while spatial interference significantly reduced spatial but not visual performance in both groups. Collectively, these findings provide evidence for two separate components of the visuospatial sketchpad (visual and spatial; Baddeley, 1966; Jacquemot, Dupoux, Decouche, & Bachoud-Levi, 2006).

### Central Executive

The central executive (CE) construct expands Norman and Shallice's (1986) two-level behavior control model that suggested willed and automatic actions are controlled at different levels depending on task difficulty. An automatic action will operate at a lower level while a novel reaction requires a higher system of processing (Baddeley, 1996). Although the central executive was initially described as a limited capacity system that controlled the two slave systems (phonological system and visuospatial sketchpad; Baddeley), more recent findings indicate that the central executive has a much more vital role in working memory. The central executive is a domain general system involved in focusing attention, dividing attention (Baddeley, 1996; Baddeley, Baddeley, Bucks, & Wilcock, 2001; Bourke, Duncan, & Nimmo-Smith, 1996), switching attention between tasks (Bourke, Duncan, & Nimmo-Smith, 1996), and coordination of phonological and visuospatial storage/rehearsal components (Bourke, Duncan, & Nimmo-Smith).

### Neuropsychological Support

Extant neuropsychological evidence provides strong support for Baddeley's model. For example, previous studies found that patients with traumatic brain injuries or surgical lesions demonstrated intact long-term memory that was not affected by short-term memory deficits, suggesting the two systems function independently (Shallice & Warrington, 1970; Vallar & Baddeley, 1984). Recent studies that utilize fMRI and PET scans suggest articulatory rehearsal is associated with the frontal lobe, the phonological buffer is located in the temporo-parietal area of the left hemisphere, and the visuospatial sketchpad is associated primarily with the right hemisphere (Paulesu, Frith, & Frackowiak, 1993; Suchan, 2008). Additionally, neuroimaging studies of patients with brain lesions indicate the visual-object and spatial components of the sketchpad are associated with distinct regions of the brain. The visual-object component is associated with the occipital lobe, while the parietal lobe is associated with the spatial component (Jonides et al., 1993; Smith and Jonides, 1997). Finally, the frontal lobe is implicated in the integration and coordination of the visual and spatial components (Smith, Jonides, Koeppe, 1996).

### Episodic Buffer

The episodic buffer is a relatively nascent structure to Baddeley's working memory model, and primarily functions as an interface between the phonological loop, visuospatial sketchpad, central executive and long-term memory. Although support for the episodic buffer has been provided by studies of sentence span (Baddeley, Vallar, & Wilson, 1987; Vallar & Baddeley, 1984), the ability to memorize large amounts of information through *chunking* (Miller, 1956; Miller & Selfridge, 1950), and the need for common storage between the phonological loop and the visuospatial sketchpad (Chincotta, Underwood, Abd Ghani, Papadopoulou, & Wresinksi, 1999), this construct is still considered a conceptual tool that has not been formally adopted as a component of the model (Baddeley, 2001).

## Working Memory in Current Models of ADHD

### Cognitive-Energetic Model

Contemporary models of ADHD emphasize cognitive and neurological deficits and are distinguished by their unique explanation of behavioral outcomes (Rapport et al., 2009). For instance, the cognitive-energetic model (CEM) of ADHD consists of a three-level information processing system (Sergeant et al., 1999). The first level separates attention into encoding, visual search, decision and orientation to stimuli. Three energetic pools - effort, arousal, and activation- encompass the second level. *Effort* is the energy required to complete a task and is influenced by cognitive load and motivation. Increased cognitive load and low motivation requires greater effort, while decreased cognitive load and high motivation requires less effort. The arousal pool influences responses based on stimulus intensity and novelty. Novel-intense stimuli necessitate increased arousal while more familiar and less intense stimuli requires less arousal. The final energetic pool, *activation*, relates to one's physiological readiness to respond and is associated with alertness, preparation, and time of day (Sergeant et al.). The CEM also includes an overarching executive system that is associated with planning, organizing, and detection and correction of errors.

The CEM suggests that deficits associated with ADHD are hypothesized to occur at all three levels of functioning (Sergeant, 2005). Disinhibition, for example, may be linked to deficits in energetic pools, specifically activation and effort, which are associated with response output. Working memory deficits do not have a causal role in this model and are downstream of effort, arousal, and activation.

The CEM lacks external validation as it is particularly challenging to experimentally test the existence of the activation pools, or whether they are causally related to behavior deficits. Consequently, it is difficult to make conclusive statements regarding the model's role in cognitive and neurological deficits (Johnson, Wiersema, & Kuntsi, 2009).

### Dual Pathway Inhibition Model

A second model, Sonuga-Barke's (2003) dual pathway inhibition model of ADHD, hypothesizes that the ADHD phenotype results from difficulty withholding responses in the presence of a prepotent response (behavioral disinhibition) or when contingencies are delayed (delay aversion). Extant studies have provided support for inhibition deficits of prepotent responses in children with ADHD, as evidenced by the Stop-Signal Task, Go-No-Go Task, and Conners' Continuous Performance Test (Oosterlaan et al., 1998; Schachar et al., 2000).

Delay aversion is an acquired motivation style in which one prefers a smaller, immediate reward over larger, delayed rewards (Sonuga-Barke, 2003; Sonuga-Barke, Wiersema, van der Meere, & Roeyers, 2009). This propensity towards immediate contingencies in children with ADHD is expressed as impulsive behavior or an inability to *delay gratification* (Marco et al., 2009). Findings that suggest reward preference is most influenced by differences in pre reinforcement delays and not contingent upon reinforcement amount provide support for the delay-aversion hypothesis (Cardinal et al. 2001; Forbes et al., 2009; Marco et al., Schott et al., 2008). The relationship between working memory and delay aversion has not been examined, and further research is needed.

According to Sonuga-Barke’s model, working memory deficits operate downstream from disinhibition. Recent research, however, challenges this central assumption of the model. A recent meta-analytic review and follow-up experimental study found that children with ADHD do not exhibit significantly impaired behavioral inhibition processes relative to typically developing children, after controlling for basic attentional processes associated with the central executive component of working memory (Alderson et al., 2007; Alderson et al., 2008). Additionally, a more recent study found that working memory, particularly the central executive, fully mediated between-group differences in inhibition (Alderson, Rapport, Hudec, Sarver, & Kofler, 2010).

### Behavioral Inhibition Model

Similar to Sonuga-Barke’s dual-pathway model, Barkley’s (2007) model of ADHD suggests that inhibition deficits such as inhibition of a prepotent or ongoing response, interference control, and delay of gratification, are a central core component of the disorder and upstream of other executive functions such as self-control, speech internalization, reconstitution, and working memory (Johnson, Wiersema, Kuntsi, 2009). Although the inhibition model of ADHD recognizes the role of working memory and other executive functions in the expression of ADHD, its identification of inhibition as a core deficit of the disorder is in conflict with recent findings from meta-analytic (Alderson et. al., 2007) and experimental studies (Alderson et al., 2008; 2010). To this end, Barkley’s inhibition model of ADHD suffers many of the same weaknesses as Sonuga-Barke’s dual-pathway model.

## Rapport’s Model of ADHD

### Overview

The functional working memory model of ADHD (Rapport et al., 2001; 2008) was posited following a previous review that examined a broad range of executive function measures and found tasks that placed relatively high demands on working memory, particularly the phonological loop, were the most reliable instruments for differentiating ADHD and typically developing groups (Rapport et al., 2000). In contrast to prevailing models that do not consider working memory (Sergeant, 2005) or suggest working memory deficits occur secondary to disinhibition (Barkley, 2007; Sonuga-Barke, 2003), the functional working memory model hypothesizes that working memory is a central core component of the disorder that is upstream of phenotypic features such as inattention, hyperactivity, and impulsivity (Rapport, Chung, Shore, & Isaacs, 2001). The working memory model of ADHD suggests that etiological factors such as *catechol O-methyl transferase* (COMT) alterations and dopamine dysregulation cause a disruption in brain development, specifically increased theta wave activity, decreased blood flow to the frontal lobe, striatal lesions, and dopamine deficiency. These neurological abnormalities result in cortical underarousal and ultimately deficits in the endophenotype (i.e. working memory; Castellanos & Tannock, 2002). Children with ADHD exhibit increased motor activity relative to typically developing peers in an attempt to increase cortical arousal needed for task demands related to central executive functioning, and/or increase input of novel stimuli (stimulation-seeking behavior) to augment or replace representations of previous stimuli that quickly fade from memory. Hyperactivity may also reflect escape behavior (e.g. out-of-seat behavior) when the demands of a task exceed the child’s working memory capacity (Rapport et al., 2001; 2008).

Previous studies of neurological correlates provide strong evidence supporting Rapport's model of ADHD. Loo and Barkley (2005) discovered that children with ADHD exhibited evidence of cortical underarousal, operationalized as increased theta wave (slow) and diminished beta (fast) wave activity, in the prefrontal cortex when engaging in experimental tasks. Additional support for the WM model is reflected in studies demonstrating working memory performance differences between children with ADHD and typically developing children, and the relationship between working memory processes and DSM-defined core deficits of the disorder (i.e., hyperactivity and inattention). Rapport et al., (2008) examined central executive, visuospatial, and phonological working memory processes in boys with ADHD and typically developing controls, and found that children with ADHD performed significantly worse across all domains. Between-group effect size estimates were exceptionally large across working memory components (i.e. Hedges' g of 2.8, 0.9, and 0.6, respectively), and much greater than effect sizes found for most other executive function tasks (Willcutt et al., 2005). A second study provided evidence of a functional relationship between working memory demands and activity (Rapport et al., 2009).  Typically developing children and children with ADHD both exhibited increased motor movement while engaging in working memory tasks relative to baseline measures, and both groups' motor activity increased as a function of increased working memory demand (set size). Additionally, children with ADHD exhibited a greater increase in activity from control to working memory conditions, relative to their typically developing peers. Findings from this study demonstrate a functional relationship between increasing working memory demands and excessive activity, which contrasts inhibition models of ADHD that suggest activity is a relatively ubiquitous feature of the disorder. Kofler et al. (2010) demonstrated that increased working memory load was directly related to decreased attention during WM tasks. Specifically, central executive processes were responsible for deficits in attentive behavior in children with ADHD, but only exhibited a small role in the attention of typically developing children (16% and 3%, respectively). Finally, Alderson et al., (2010) found that visuospatial working memory fully mediated the relationship between group (ADHD, TD) and behavioral inhibition. Collectively, findings from these studies provide strong evidence for working memory as a candidate core deficit or endophenotype of ADHD and suggest that inhibition processes are downstream of working memory.

## Previous Reviews of Working Memory in ADHD

To date, three previous meta-analytic reviews have examined working memory in children with ADHD. The first examined 46 studies of executive functions in children with ADHD, conduct disorder, autism, and Tourette syndrome (Pennington & Ozonoff, 1996). Children with ADHD performed comparably to typically developing children on verbal and visuospatial memory tasks. Twenty-three percent of studies measuring verbal memory found significant between-group differences between ADHD and the control group, while 21 percent of studies measuring visuospatial memory found significant between-group differences between ADHD and the control group. A second meta-analytic review of 83 studies published between 1980 and 2004 examined executive function deficits in children and adolescents with ADHD (Willcutt et al., 2005). Seventy-five percent of studies that examined spatial working memory found significant between-group differences comparing children with ADHD to typically developing controls, while

55 percent that examined verbal working memory found significant between-group differences.

A more recent meta-analytic review of 26 studies examined working memory in ADHD by parsing tasks into four categories: verbal storage, verbal central executive (CE), spatial storage, and spatial central executive (Martinussen, Hayden, Hogg-Johnson, & Tannock, 2005). A moderate effect size between control and ADHD groups on verbal storage tasks (ES=0.47, CI=0.36-0.59) and verbal CE tasks (ES=0.43, CI=0.24-0.62) and a large effect size between control and ADHD groups on spatial storage tasks (ES=0.85, CI=0.62-1.08) and spatial CE tasks (ES=1.06, CI=0.72-1.39) indicated children with ADHD performed significantly worse on WM tasks relative to typically developing children. Additionally, larger effect sizes were found in spatial storage and spatial CE tasks, while moderate between-group effect sizes were found in verbal storage and verbal CE tasks (Martinussen, Hayden, Hogg-Johnson, & Tannock).

Despite strong evidence from these previous reviews (Willcutt et al., 2005; Martinussen, Hayden, Hogg-Johnson, & Tannock, 2005) and more recent experimental investigations that reported exceptionally large magnitude between-group (ADHD, TD) differences in WM performance (Rapport et al., 2008; 2009: ES = 1.49 – 3.03), several studies have suggested that working memory deficits are not a core component of ADHD because the impairments are not universal in affected children. For example, Rucklidge and Tannock (2002), Toplak et al. (2003), and Willcutt et al. (2001) failed to find significant working memory differences between children with ADHD and typically developing children. Several previously unexamined methodological and sample variables, however, may account for the small or non-significant working memory differences in previous studies and inconsistent findings across previous reviews.

# CHAPTER III

# PRESENT STUDY

The current study updates previous meta-analytic reviews (Martinussen et al., 2005; Willcutt et al., 2005) with the inclusion of 35 new studies. Seven of the original 26 studies from Martinussen and colleagues were included based on the current inclusion criteria, as well as 35 additional studies for a total of 42 studies. Further, this is the first meta-analytic review to examine the potential moderating effects of a variety of subject (samples' sex ratio, age and diagnostic classification method) and task (the number of trials per set size, the performance metric, response modality, simple mental manipulation, and CE demands) variables on WM deficits in children with ADHD compared to typically developing children. Examination of potential moderating variables is essential due to their potential influence on within- and between-study effect size variability (Holmbeck, 1997). In addition, significant moderators may explain heterogeneity within- and between-study findings that have suggested WM is not a core deficit of ADHD. For an extended review of the literature, see Appendix A.

## Hypotheses

Hypothesis I: A significant between-group effect size for PH and VS working memory tasks was expected when comparing the ADHD and typically developing groups. This hypothesis is based on previous meta-analytic reviews of working memory (Martinussen et al., 2005; Pennington & Ozonoff, 1996) and an exceptionally large magnitude effect sizes reported by Rapport et al. (2008).

Hypothesis II: A larger overall VS effect size was expected relative to the PH effect size. This prediction is based on extant meta-analytic (Martinussen et al., 2005) and experimental (Rapport et al., 2008) findings.

Hypothesis IIIa: Previous studies suggest that females are more likely to present with attention deficits rather than hyperactive/impulsive symptoms. Studies that include higher percentages of females were expected to have smaller magnitude effect sizes based on previous literature suggesting executive function deficits are less pronounced in females (Froehlich, 2007; Lee, Oakland, Jackson, & Glutting, 2008).

Hypothesis IIIb: Extant studies suggest that working memory improves with age among all children (Alderson, Rapport, Sarver, & Kofler, 2008), and children with ADHD exhibit working memory functioning similar to younger children (Alderson, Rapport, Sarver, & Kofler). Studies that included younger children were expected to have larger between-group effect sizes relative to studies with older samples (Rapport et al., 2008).

Hypothesis IIIc: Studies that do not rely on rigorous diagnostic methods (i.e., relying exclusively on rating scales) were expected to decrease group membership homogeneity and increase between-group heterogeneity (Rapport et al., 2000). Therefore, studies that relied on rigorous diagnostic methods, such as clinical interviews and ratings scales were expected to report larger between-group effect sizes relative to studies that relied on ratings scale alone.

Hypothesis IIId: Studies that rely on relatively few trials per set size may not effectively capture between-group differences of working memory (Rapport et al., 2008). Studies that relied on a greater number of trials per set size were expected to find large between-group effect sizes.

Hypothesis IIIe: Working memory performance accuracy is typically defined as either total correct trials or total correct stimuli, with the number of total correct trials currently being the most frequent approach to measuring working memory performance (e.g. digit span tasks). Examination of total correct trials as a dependent measure, however, may not provide the most valid measure of participants' working memory abilities because discontinuing a task after a predetermined number of incorrect trials (e.g., after two incorrect trials on digit-span tasks) discards potential correct answers on subsequent trials, and consequently underestimate one's working memory ability (Conway, Cowan, & Bunting, 2001). Studies that utilized stimuli as performance metric were expected to find larger between-group effect sizes compared to studies that used trials as the dependent measure.

Hypothesis IIIf: Extant literature suggests that recall tasks place greater working memory demands on children because they require more effortful, self-initiated processes, compared to the simpler task of choosing the stimulus among a group of options (recognition task; Baddeley, Chincotta, Stafford, Turk, 2002; Craik & McDowd, 1987). Consequently, studies that utilized recognition tasks were expected to find non-significant or small effect sizes relative to studies that utilize recall tasks, due to less demand placed on the working memory system.

Hypothesis IIIg: Studies that required attentional shift between the stimuli and the processing component of the task above and beyond simple reversal of stimuli (e.g., involve the CE system; Engle et al., 1999) and studies that required simple manipulation of stimuli (e.g., reversal of stimuli) were expected to find larger between-group effect sizes compared to those that did not place demands on the CE or require simple manipulation, respectively.

# CHAPTER IV

# METHOD

## Literature Searches

Literature searches were performed using the MEDLINE, PsycARTICLES, and PsycINFO databases. The following keywords were utilized: attention deficit disorder, ADHD, hyper* and atten*, each of which was paired with working memory, visual span, spatial span, short-term memory, phonological loop, visuospatial, and digit span. An asterisk following a root word instructed search engines to look for any derivative of the word that is followed by the asterisk (e.g., hyper*: hyperactive, hyperactivity). Studies that were cited in the studies obtained from the initial search were examined (backward search), and a forward search was conducted using the Social Science Citation Index to locate relevant studies that cited the included studies of working memory in children with ADHD.

## Inclusion Criteria

Articles were included if they utilized a task that required short-term mental storage of verbal or visuospatial information. Additional inclusion criteria required: (1) Sample of children and early adolescents ages 8-16 years; (2) Inclusion of a typically developing control group; (3) Inclusion of phonological and/or visuospatial scores (rather than one composite score that reflects an aggregate of phonological and visuospatial performance); (4) Only between-subjects comparisons; (5) Published article (e.g., not a dissertation); (6) Included adequate data to calculate an effect size for between-group working memory performance differences (e.g. studies were excluded that reported event-related potentials recorded during working memory tasks); and (7) Study was written in English.

The age range of 8-16 years was selected based on developmental differences in cognitive strategies and processes observed in children and adolescents relative to adults (Ang & Lee, 2008; Lemaire & Callies, 2009). Phonological and visuospatial effect sizes were computed and examined separately due to extensive neuropsychological (Baddeley, 2007), neuroanatomical (Smith, Jonides, & Koeppe, 1996), neuroimaging (Fassbender & Schweitzer, 2006), and factor analytic (Alloway, Gathercole, & Pickering, 2006) investigations that support the distinct functioning of the two subsystems. Also, computing an overall effect size from both phonological and visuospatial tasks may omit phonological or visuospatial data, since only one data point can be used for each study. That is, multiple effect sizes derived from the same sample risk threats to statistical independence and overweight findings from a single sample (Lipsey & Wilson, 2001).

Multiple effect sizes were included from the same study, however, if they provided sufficient data to calculate independent phonological and visuospatial effect sizes (one score for each modality).

In an effort to include only one task from a study in a single modality, multiple tasks fitting criteria for the same condition were omitted based on a priori guidelines. Specifically, preference was given to study conditions that provided the most complete data since incomplete data results in exclusion from later moderation analyses[1]. As a next step, conditions that placed greater demands on working memory (e.g., Letter-Number Sequencing; McGurk et al., 2004), particularly the CE, were given preference over conditions that reflected simple storage/rehearsal processes (e.g., Digit Span Forward). A third step gave preference to any task that required simple mental manipulation of information (e.g., Digit Span Backwards; Rosen & Engle, 1997). Finally, studies were selected randomly by a coin toss when task demands were equivalent and none of the a priori selection guidelines provided resolution.

The initial search resulted in 130 studies. Eighty-eight studies did not meet criteria for inclusion and were therefore excluded from the meta-analysis. Of the remaining 42 studies, 29 reported data from several experimental tasks/conditions. Data from 21 simple-storage tasks were not included in favor of data from tasks that required mental manipulation of temporarily stored information. An additional 7 studies reported data from multiple tasks/conditions that did not differ with regard to predetermine inclusion criteria. As a result, one task/condition was randomly chosen from each of the five studies by flipping a coin. Finally, one study (Karatekin, 2004) provided nine

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[1] The weighted regression used to examine potential moderation effects deletes cases listwise so that any missing data from a single study results in exclusion from the analysis.

experimental conditions with three set sizes and post-stimulus delays. We included data from the condition with the second largest set size and delay (set size 7, 6 second response time) to best reflect the overall aggregate findings.

Collectively, 42 studies provided sufficient data to examine 31 and 28 samples' phonological and visuospatial working memory performance, respectively. Hedges *g* effect sizes were calculated with means and standard deviations for thirty phonological studies and twenty-seven visuospatial studies. Sample size and Pearson *r* was used to calculate the effect size for one visuospatial and one phonological task (Alderson, Rapport, Hudec, Sarver, Kofler, 2010). See Table 1 for a complete list of studies and included moderating variables.

### *Moderators*

*Percent Female*. The ADHD phenotype frequently presents differently in females and males. For example, females are more likely to exhibit attention difficulties in the absence of hyperactivity-impulsivity symptoms, which are typically present in boys with the disorder (Abikoff et al., 2002; Biederman & Faraone, 2004; Graetz, Sawyer, & Baghurst, 2005). In addition, previous research suggests that executive function (e.g. working memory) deficits in females are less severe relative to deficits present in boys (Seidman, Biederman, Faraone, & Weber, 1997), and unlike their male counterparts, females with ADHD exhibit less decreased neural activity in the prefrontal regions associated with working memory (Valera et al., 2010). These findings suggest that studies with samples consisting of a high percentage of ADHD females are expected to find smaller magnitude between-group differences relative to studies that utilized predominantly male samples. Consequently, the percent of female participants in the

ADHD group was examined as a moderator to determine if small magnitude or non-significant findings in previous experimental and meta-analytic studies can be explained by gender differences in ADHD. The percentage of females in the ADHD group included in each study was analyzed as a continuous moderating variable.

*Age*. Extant studies suggest that working memory tends to emerge rather early in life, continues to develop until about 13-15 years (Brocki & Bohlin, 2004; Brocki & Bohlin, 2006; Korkman, Kemp, & Kirk, 2001), and improves with age among both children with ADHD and typically developing children (Klingberg, Forssberg, & Westerberg, 2002; Van der Molen, Van Luit, Van der Molen, Klugkist, & Jongmans, 2010). Further, children with ADHD exhibit working memory functioning similar to younger children (Brocki & Bohlin, 2006), suggesting studies that include samples of older children are expected to find smaller effects, as older children with ADHD would have more time to developmentally “catch up” to their non-affected peers. The overall sample’s mean age was analyzed as a continuous moderating variable.

*Diagnostic Method*. Previous meta-analytic reviews have not examined whether differences in group assignment methodology moderate between-group (ADHD, typically developing) effect size estimates of WM performance. Grouping criteria may vary from reliance on single-source narrow band ratings scales (Kilic, Sener, Kockar, & Karakas, 2007; McInerney, Hrabok, & Kerns, 2005; McInnes, Humprhies, Hogg-Johnson, & Tannock, 2002) to a more comprehensive  approach that includes psychosocial interview, structured- or semi-structured clinical interview, and multiple informant (parent and teacher) parent and teacher ratings scales (Bental & Tirosh, 2007; Pasini, Paloscia, Alessandrelli, Porfirio, & Curatolo, 2007; Passolunghi, Marzocchi, &

Fiorillo, 2005). The latter comprehensive method is considered the *gold standard* (Power, Costigan, Leff, Eiraldi, & Landau, 2001) in diagnosing ADHD and is advantageous due to the non-pathognomic nature of ADHD-related symptoms (inattention and restlessness; Furman, 2005). Studies that rely on a single source of information (e.g., only rating scales) to group participants are expected to be associated with smaller working memory effect size estimates, relative to studies that utilize more comprehensive diagnostic procedures, such that relying on only rating scales may inadvertently include non-ADHD children in the ADHD group.  A dichotomous variable, *Diagnostic Method,* was created by categorizing studies as simple (e.g., only rating scales or professional opinion; coded as 0) or comprehensive (i.e., semi-structured or structured interview and parent/teacher ratings scales; coded as 1).

*Trials Per Set Size*. Studies that utilize relatively few trials are expected to be less reliable since multiple trials can be averaged in an effort to reduce error (Bland & Altman, 1996) and the use of fewer trials is associated with lower internal consistency (Welsh, Revilla, Strongin, & Kepler, 2000). Furthermore, extant research suggests demands on working memory may have a cumulative effect, such that WM resources are depleted after multiple trials and an adequate number of trials must be included to provide a valid measure of learning (Stepanov, Abramson, Wolf, & Convit, 2010); that is, studies with relatively few trials are expected to put fewer demands on WM resources relative to studies with many trials (Burton & Daneman, 2007). Collectively, studies that rely on relatively few trials per set size may not effectively capture between-group working memory differences and are expected to find smaller between-group effect sizes relative to studies that included greater trials per set size (Rapport et al., 2008). A dichotomous moderating variable, *Trials Per Set Size*, was created by categorizing studies that included fewer than ten trials per set size as “low” [coded as (0)], and studies that included  greater than ten trials per set size as “high” [coded as (1)]. Ten was chosen to demarcate studies so the current study could differentiate between single digit and double digit trials.

*Performance Metric.* Working memory performance accuracy is typically defined as either total correct trials or total correct stimuli, with the number of total correct trials currently being the most frequent approach to measuring working memory performance (e.g. digit span tasks). Examination of total correct trials as a dependent measure, however, may not provide the most valid measure of participants’ working memory abilities because discontinuing a task after a predetermined number of incorrect trials (e.g., after two incorrect trials on digit-span tasks) discards potential correct answers on subsequent trials, and consequently underestimate one’s working memory ability (Conway, Cowan, & Bunting, 2001). For example, although a child may have the ability to recall 5 stimuli, external factors such as momentary distraction or lack of motivation during a smaller set size, may result in errors that lead to a discontinued test and an underestimate of their maximum storage capacity. Examination of the performance metric as a moderator may explicate whether small or non-significant effect sizes reported in previous studies may be explained by the use of total trials correct as a dependent measure. Previous meta-analytic reviews have not examined whether the dependent variable used to measure performance influences the magnitude of effect size. Consequently, the moderating variable *Performance Metric* was created by coding studies as trials correct (0) or stimuli correct (1).

*Response Modality*. Recall and recognition tasks rely on separate cognitive processes (Kahana, Rizzuto, & Schneider, 2005) and are correlated with discreet neurological structures located in the anterior cingulate, thalamus, globus pallidus, and cerebellum (Cabeza et al., 1997). Recall tasks place greater working memory demands on children because they require more effortful, self-initiated processes, compared to the simpler task of choosing the stimulus among a group of options (recognition task; Baddeley, Chincotta, Stafford, Turk, 2002; Craik & McDowd, 1987). Consequently, studies that utilize recognition tasks are expected to find non-significant or small effect sizes relative to studies that utilize recall tasks, due to less demand placed on the working memory system. *Response Modality* (i.e., recall or recognition) was examined as a moderating variable to determine if small or non-significant effect sizes may be explained by the use of recognition rather than recall tasks. Studies were categorized into those that included recognition tasks (0) and those that included recall tasks (1) as their measure of working memory.

*Simple Manipulation (SM)* and *CE Demand (CED)*. Extant studies traditionally reify tasks that require temporary storage, maintenance, and manipulation of phonological or visuospatial information as measures of working memory (Luciana, Conklin, Hooper, & Yarger, 2005; Passolunghi & Mammarella, 2010). Examples of these tasks include Digit Span-Backwards and Letter-Number Sequencing from the Wechsler scales (Wechsler, 2003) and Finger Windows-Backward from the Wide Range Assessment of Memory and Learning (WRAML; Sheslow & Adams, 2003). Previous experimental (Lambek et al., 2010; Rucklidge & Tannock, 2002; Toplak, et al., 2003; Willcutt et al., 2001) and meta-analytic (Martinussen et al., 2005; Willcutt et al., 2005) reviews have adopted this rationale to examine the difference between tasks that provide a measure of storage and those that require manipulation (i.e. involve the CE). The latter tasks are categorized as working memory since they require the participant to remember stimuli and later recall the stimuli in a different pattern than the original presentation. The potential moderator variable *Simple Manipulation* was created by dichotomously coding studies as 0 (no manipulation requirement) or 1 (required manipulation).

More recent factor-analytic (Reynolds, 1997), meta-analytic (Verhaeghen, Marcoen, & Goosens, 1993), and structural equation model (Engle et al., 1999) studies suggest that performance on backwards span tasks (e.g., Digit Span Backwards that require the participants to repeat a sequence of stimuli in the opposite order that it was presented; Wechsler, 2003) reflect short-term storage processes rather than working memory. That is, simple reversal of stimuli does not appear to place sufficient demand on the CE component of working memory. Consequently, previous meta-analytic reviews that have included backwards span tasks as measures of WM may have found small or nonsignificant between-group differences (ADHD vs. typically developing) because simply rearranging stimuli likely only requires STM (and not working memory) processes (Engle et al., 1999). To examine differences of working memory and simple storage/rehearsal processes based on recent findings, a second regression model was run for each outcome measure, PH and VS, using the moderator variable *CE Demand* in place of the variable *Simple Manipulation*. Specifically, studies that require attentional shift between the stimuli and the processing component of the task above and beyond simple reversal of stimuli (e.g., involve the CE system; Engle et al., 1999), were categorized as working memory tasks (1), while those that did not (e.g. Digit Span Backwards) were placed in the short-term memory category (0).

## Data Analytic Strategy

### Effect Size Estimation

Effect size estimates were computed using Comprehensive Meta-Analysis software. Positive effect sizes indicate higher mean scores for the control group relative to the ADHD group, while negative effect sizes indicate lower mean scores for the control group relative to the ADHD group. Hedges' *g* effect sizes were used in the current meta-analysis since the metric weights each effect size by its standard error. Weighting each effect size by its respective standard error corrects the problem of equal weight given to effect sizes of small and large samples (Lipsey & Wilson, 2001). Effect sizes are classified as small (ES ≤ 0.30), medium (0.30 < ES < 0.67), or large (ES ≥ 0.67), whereas an ES of zero indicates no difference between means (Lipsey & Wilson, 2001). While most studies reported accuracy (number of trials or stimuli correct) as their dependent variable, several studies reported errors (number of trials or stimuli incorrect). The direction of the effect size of the latter studies was reversed to provide uniform effect size data (e.g., an effect size of -0.46 was changed to 0.46).

### Publication Bias

Fail-Safe N Analyses were performed to determine the likelihood that missing/unpublished studies may reduce the confidence interval of the effect size to include zero (i.e. result in no significant differences in ADHD and control groups). The

Fail-safe N approach is commonly used in meta-analytic studies (Lipsey & Wilson, 2001).

## Homogeneity Analyses

A *Q*-test was performed on each outcome variable (Phonological WM and Visuospatial WM) to examine the effect size distribution of the studies. A significant *Q* rejects the assumption of homogeneity and supports the examination of potential moderator effects (Lipsey & Wilson, 2001).

## Moderator Analyses

A fixed-effects weighted regression approach using SPSS for Windows 18.0 was used to provide a measure of overall fit ($Q_R$), as well as an error/residual term ($Q_E$). A significant $Q_R$ indicates that the model accounts for significant variability among effect sizes, while a significant $Q_E$ indicates that the residual variance is greater than what is expected from random study-level sampling error (Lipsey & Wilson, 2001). Both statistics are distributed as chi-square.

Effect size estimates in a meta-analysis are not expected to fall on a normal distribution. Consequently, beta-weights from each regression were corrected and compared to a z-distribution. Specifically, the standard error of the beta-weight was divided by the square root of the mean square of the residual. Next, the beta-weight was divided by the corrected standard error of the beta-weight and this z-value was compared to a z-table to determine if the moderator was statistically significant (Lipsey & Wilson, 2001).

## Best Case Estimation

Best case estimation involves solving the regression equations derived from the four previous moderation analyses (i.e., PH-WM with manipulation variable, PH-WM with CE Demand variable, VS-WM with manipulation variable, VS-WM with CE demand variable), with levels of each moderator that is considered best practice according to empirical research (Lipsey & Wilson, 2001). Best case methodological variables include fewer females, younger children, comprehensive diagnostic criteria, larger number of trials, recall tasks, and stimuli correct.

# CHAPTER V

## RESULTS

### *Effect Sizes*

A significant medium between-group (ADHD, TD) effect size of 0.67 (95% confidence interval = 0.57 to 0.77) was calculated from thirty-one PH-WM studies and indicated children with ADHD performed moderately worse on PH-WM tasks compared to their typically developing peers. A $Q$-test (29) = 86.98, $p < 0.001$ indicated that there was significant heterogeneity among the calculated effect sizes, with effect sizes ranging from -0.40 to 2.78. A Fail-safe $N$ analysis revealed that approximately 1509 additional studies would be needed to yield an effect size with a confidence interval that included zero (i.e., no significant between-group differences of performance on PH-WM tasks).

A significant medium effect size of 0.61 (95% confidence interval = 0.50 to 0.71) was calculated from twenty-eight VS-WM studies, which indicated that children with ADHD performed moderately worse on VS-WM tasks relative to typically developing children. A $Q$ (26) = 211.02, $p < 0.001$ indicated that there was significant heterogeneity among the calculated effect sizes, with effect sizes ranging from -.28 to 5.35.

A Fail-safe *N* analysis revealed that approximately 1474 additional studies would need to be included to yield an effect size with a confidence interval that included zero (the effect would be nonsignificant).

Moderator Variables

*Phonological Working Memory (PH-WM).* The potential moderating variables Percent Female, Age, Diagnostic Method, Trials Per Set Size, Performance Metric, Response Modality, and Simple Manipulation were included in the regression equation. The results of the weighted-multiple regression indicated that the model explained a significant proportion of effect size variability ($R^2 = 0.36$) in the PH-WM effect size distribution, $Q_R = 17.95$, $df = 7$, $p < 0.001$. Two of the moderating variables significantly predicted effect size variability across the studies: Age, $z = -2.61$, $p < .001$ and Response Modality, $z = -1.75$, $p < .05$. Studies that included younger children and recognition tasks were associated with larger between-group differences. A significant sum-of-squares residual, $Q_E = 31.42$, $df = 18$, $p < 0.001$, indicated that unexplained variability was greater than would be expected from sampling error alone.

A second weighted regression was completed that included the moderating variable CE Demand in place of Simple Manipulation. The results of the weighted-multiple regression indicated that the model explained a significant proportion of effect size variability ($R^2 = 0.36$) in the PH-WM effect size distribution, $Q_R = 17.62$, $df = 7$, $p < 0.001$. However, only one moderating variable, Age, $z = -2.74$, $p < .001$, significantly predicted effect size variability across the studies. Studies that included younger children were associated with larger between-group differences. A significant sum-of-squares residual, $Q_E = 31.74$, $df = 18$, $p < 0.001$, indicated that unexplained variability was greater than would be expected from sampling error alone.

*Visuospatial Working Memory (VS-WM).* The potential moderating variables Percent Female, Age, Diagnostic Method, Trials Per Set Size, Performance Metric, Response Modality, and Simple Manipulation were included in the regression equation. The results of the weighted-multiple regression indicated that the model explained a significant proportion of effect size variability ($R^2 = 0.28$) in the VS-WM effect size distribution, $Q_R = 39.54$, $df = 7$, $p < 0.001$. Five of the moderating variables significantly predicted effect size variability across the studies: Age, $z = -2.29$, $p < .01$; Diagnostic Method, $z = -2.38$, $p<.001$; Response Modality, $z = -2.21$, $p<.05$; Trials Per Set Size, $z = -2.63$, $p<.001$; and Performance Metric, $z = 2.87$, $p<.001$. Studies that included younger children, less comprehensive diagnostic measures, recall tasks, a larger number of trials, and stimuli correct as the dependent measure were associated with larger between-group differences. A significant sum-of-squares residual, $Q_E = 99.53$, $df = 15$, $p < 0.001$, indicated that unexplained variability was greater than would be expected from sampling error alone.

A final weighted regression was completed that included the moderating variable CE Demand in place of the variable Simple Manipulation. The results of the weighted-multiple regression indicated that the model explained a significant proportion of effect size variability ($R^2 = 0.31$) in the VS-WM effect size distribution, $Q_R = 43.13$, $df = 7$, $p < 0.001$. All seven of the moderating variables significantly predicted effect size variability across the studies: Percent Female, $z = -1.79$, $p < .05$; Age, $z = -2.35$, $p < .001$, Diagnostic Method, $z = -1.92$, $p < .05$; Trials Per Set Size, $z = 2.79$, $p < .01$; Response Modality, $z =$

2.69, $p < .01$; Performance Metric, $z = 2.93$, $p < .01$; and CE Demand, $z = 2.17$, $p < .01$. Studies that included fewer females, younger children, less comprehensive diagnostic methods, higher number of trials per set size, recall tasks, stimuli correct, and working memory tasks that placed demand on the CE were associated with larger between-group differences. A significant sum-of-squares residual, $Q_E = 95.94$, $df = 15$, $p < 0.001$, indicated that unexplained variability was greater than would be expected from sampling error alone (see Table 2).

### Best Case Estimate

Solving the regression equations for PH-WM and VS-WM studies with values to provide a best case estimate suggested that effect sizes of 0.85 and 1.47, respectively, are expected when studies use a comprehensive diagnostic assessment, more than 10 trials per set size, recall tasks, stimuli as the dependent variable, and require cognitive manipulation of temporarily stored information. Two additional regression equations were solved using the moderating variable CE Demand in place of the variable Simple Manipulation. The solved regression equations for PH-WM and VS-WM studies suggested that effect sizes of 0.83 and 1.83, respectively, are expected when using best practice procedures.

### Percent Overlap

An overlap statistic (OL%; Zakzanis, 2001) was calculated to examine the amount of expected overlap in working memory performance between the ADHD group and typically developing group, if the best case methodology is used. Given the best case estimate, the visuospatial working memory performance of children with ADHD is only expected to overlap the performance of typically developing children by 22.6% to 29.30%. In addition, there is a 92% to 96% chance that the visuospatial performance of children with ADHD will be below the mean score of children in the typically developing group. The overlap of phonological working memory performance between children with ADHD and typically developing children is expected to be larger given estimates of 48.4% to 52.6%. However, there is an estimated 79% to 82% chance that children with ADHD would exhibit phonological working memory performance that is below the average score of children in the typically developing group (see Table 3).

# CHAPTER VI

## DISCUSSION

The current study updates previous meta-analytic reviews (Martinussen et al., 2005; Willcutt et al., 2005) with the inclusion of 35 new studies. Seven of the original 26 studies from Martinussen and colleagues were included based on the current inclusion criteria, as well as 35 additional studies for a total of 42 studies. In addition, the current study is the first meta-analysis to examine potential moderator variables such as Percent Female, Age, Diagnostic Method, Trials Per Set Size, Performance Metric, Response Modality, Simple Manipulation, and CE Demand. Examination of potential moderating variables is important due to their ability to explain effect size variability across studies, and may explicate why previous meta-analytic (Martinussen et al., 2005; Willcutt et al., 2005) and experimental studies (Lambek et al., 2010; Rucklidge & Tannock, 2002; Toplak et al., 2003; Willcutt et al., 2001) have not found uniform between-group (ADHD and TD) working memory differences.

Overall, studies that examined phonological and visuospatial-working memory tasks yielded significant moderate to large effects (0.67 and 0.61, respectively), which indicate that children with ADHD generally demonstrate poorer performance on phonological and visuospatial working memory tasks relative to typically developing children. The magnitude of the current findings is similar to Willcutt et al.'s (2005) previous meta-analytic review that reported ESs of 0.75 and 0.59 for visuospatial and phonological working memory, respectively. Our findings were also consistent with phonological effect size estimates reported by Martinussen et al. (2005), but incrementally smaller relative to their visuospatial effect sizes of 0.85-1.06. The discrepancy between the current findings and those of Martinussen and colleagues may reflect study-wide differences in task reification. That is, Martinussen and colleagues identified and grouped tasks as either storage or CE, based on mental manipulation of information required for task completion (e.g., forward span tasks were categorized as storage while backward span tasks were categorized as CE). The current study only separated tasks according to modality (VS or PH) and examined the effect of CE processes on between-group performance differences with the use of moderator variables (Simple Manipulation and CE Demand). This approach was believed to be a methodological improvement due to recent findings that suggest forward and backward span tasks likely include both storage and CE processes. Inclusion of simple storage tasks (e.g., forward span tasks) in the overall ES estimate, however, likely reduced the effect size magnitudes (Rapport et al., 2008). Finally, the similarity between the phonological and visuospatial effect sizes (ES difference of .06) in the current study is in contrast to previous meta-analytic (Martinussen et al., 2005; Willcutt et al., 2005) and experimental (Alderson et al., 2007) findings that have consistently revealed larger between-group differences in the visuospatial domain. This finding, however, may also reflect differences in task categorization, such that both storage and CE tasks were examined together in the current study. Consideration of potential moderating effects may further explicate this discrepancy.

The percent of females in included studies significantly moderated VS-WM effect size variability in both the original regression equation when Simple Manipulation was included as a moderator and the second regression equation which included CE Demand. That is, studies that included fewer females were associated with larger between-group differences in VS working memory performance, relative to those with a higher proportion of females. These findings are consistent with our a priori hypotheses and extant literature that suggests executive function (e.g., working memory) deficits are more pronounced in males compared to females (Seidman et al., 1997). The sex ratio was not a significant moderator of PH-WM performance, however, in either the original regression equation that included Simple Manipulation as a moderator, or the second regression equation that included CE Demand as a moderator. Consideration of typical working memory development, however, may explicate this finding. Specifically, extant literature suggests that most children, regardless of sex, experience a developmental shift around ages six or seven from predominantly relying on the visuospatial system to the phonological system, and the association between CE and phonological storage/rehearsal processes remains limited until at least age ten years of age (Gathercole, Pickering, Ambridge, & Wearing, 2004). The average age of participants included in the current meta-analysis was 10.66 years, suggesting that the inclusion of younger participants may have led to poorer PH working memory performance, regardless of diagnostic classification (ADHD, TD) or sex. That is, the overall young age of the included samples may have suppressed potential sex difference as both young males and females are expected to exhibit relatively poor PH performance (Gathercole et al., 2004).

Visuospatial working memory studies that relied on simple diagnostic procedures (e.g., ratings scales only) were associated with larger between-group differences in working memory relative to those that utilized comprehensive diagnostic procedures. Again, this moderator was not significant for the PH tasks. These results contradict previous literature that suggest the use of comprehensive diagnostic procedures allow for more true positives and fewer false positives (Power, Costigan, Leff, Eiraldi, & Landau, 2001), but parallel results from two previous meta-analytic reviews (Alderson et al., 2007; Kofler, Rapport, & Alderson, 2008). These seemingly paradoxical findings may be explained by considering the calculation of standardized effect size metrics. That is, the use of simple diagnostic procedures are expected to result in a more heterogeneous diagnostic group that consists of a range of psychiatric disorders (e.g., ADHD, anxiety, depression, autism), relative to more comprehensive diagnostic procedures that are expected to result in a homogenous group of children with ADHD. Children with ADHD frequently display a high rate of intra- and inter-performance variability across a broad range of experimental tasks, which is frequently reflected in greater within-group standard deviations (Johnson et al., 2007; Swanson et al., 2007; Uebel et al., 2010). Consequently, identifying a higher number of true positives likely lowered effect sizes estimates by increasing the effect size denominator ($sd_{ADHD} + sd_{Control}/2$), which reflects the pooled standard deviation between children with ADHD and typically developing children.

Consistent with our a priori hypothesis, visuospatial studies that included a larger number of trials per set size were associated with larger between-group differences, with the ADHD group performing worse compared to the typically developing children. The effect size variability across PH tasks, however, was not significantly moderated by Trials Per Set Size. This finding was in stark contrast to our original hypotheses and inconsistent with previous studies that suggest a greater number of trials offers the participant more opportunities to adequately demonstrate their working memory performance (Conway et al., 2001), and several trials can be averaged to reduce measurement error (Bland & Altman, 1996) and increase internal consistency (Welsh et al., 2000).

Visuospatial studies that included recall tasks were associated with larger between-group differences relative to studies that relied on recognition tasks, with the ADHD group performing worse compared to the TD group. Phonological tasks that utilized recall tasks where also associated with relatively larger ESs when Simple Manipulation was included as a moderating variable, but not when CE Demand was included in the regression equation. The VS-WM findings are similar to previous literature that suggests recall tasks, compared to recognition tasks, place more working memory demands on children because they require more effortful, self-initiated processes, compared to the simpler task of choosing the stimulus among a group of options (recognition task; Baddeley et al., 2007; Craik & McDowd, 1987). Our finding that recognition tasks were associated with larger ESs in PH studies, however, was surprising. Further examination of phonological-recognition tasks, however, indicates that 80% of included tasks were *n*-back tasks that require a high degree of sustainedfocused attention and mental manipulation of stimuli (Carlson et al., 1998; Schreppel, Pauli, Ellgring, Fallgatter, & Herrmann, 2008). In contrast, relatively fewer (50%) visuospatial recognition tasks required similar processing demands (e.g., visuospatial *n*-back). Consequently, the difference across modalities may be an artifact of task demands rather than differences in response modality. Further research is needed to explicate these findings.

Studies that used stimuli correct as their dependent measure (as opposed to trials correct) yielded larger VS-WM between-group differences, regardless of whether Simple Manipulation or CE Demand was included, with the ADHD group performing worse compared to their typically developing peers. Conversely, Performance Metric did not significantly moderate either regression equation for the PH-WM tasks. Stimuli Correct was expected to be a more sensitive method of assessing between-group (ADHD, TD) differences and consequently result in larger effect sizes estimates (Conway et al., 2001). That is, using stimuli correct as the dependent measure allows sufficient opportunity for participants to demonstrate their working memory capabilities compared to trials as the dependent measure, which may erroneously deflate working memory scores if the participant accurately answers some stimuli correct, but not enough for the entire trial to be correct (Conway et al., 2001).

Studies that included younger children were associated with larger between-group effect sizes in both regression equations for VS-WM and PH-WM tasks. This finding is consistent with a priori predictions and previous studies that suggest children with ADHD exhibit working memory functioning similar to younger children (Brocki & Bohlin, 2004; Brocki & Bohlin, 2006; Korkman et al., 2001). That is, studies that included samples of younger children were expected to find larger effects since children with ADHD would have less time to developmentally “catch up” to their non-affected peers. This finding is consistent with our a priori prediction and is consistent with previous literature that suggests children with ADHD exhibit poorer working memory performance relative to adults with the disorder (Brocki & Bohlin).

Simple Manipulation was not a significant moderator of effect size variability across the VS or PH tasks, while CE Demand was a significant moderator of effect size variability across VS tasks, but not PH tasks. These results parallel our hypothesis that simple manipulation of stimuli does not adequately capture between-group differences (Engle et al., 1999; Rosen & Engle, 1997), and are consistent with previous findings that suggest ADHD-related working memory deficits are predominantly attributable to CE processes (; Alderson et al., 2010; Rapport et al., 2008; Rapport et al., 2009; Martinussen et al., 2005). These findings may have profound implications for the validity of working memory measures frequently included in cognitive assessments, particularly when differential diagnosis of ADHD is influenced by between-group performance differences. It is possible that intelligence tests do not adequately capturing the working memory construct since they include tasks that do not place sufficient demand on the CE (Engle et al., 1999).

Previous meta-analytic (Martinussen et al., 2005; Willcutt et al., 2005) and experimental (Lambek et al., 2010; Rucklidge & Tannock, 2002; Toplak et al., 2003; Willcutt et al., 2001) studies have argued that working memory is not a core deficit of ADHD because they did not find significant differences in WM performance between all children with ADHD compared to their typically developing peers. The current study sought to examine potential moderating variables that may explain these small or nonsignificant between-group (ADHD vs. TD) differences. Collectively, the current study's findings suggest that several methodological and experimental conditions (e.g., younger children, stimuli correct, fewer number of females) are associated with large between-group working memory differences, while other experimental conditions (e.g., older children, trials correct, larger number of females) may suppress between-group effects. The influence of participant and task moderating variables is exemplified with findings from the best case estimates that solved each regression equation based on theoretically and methodologically best-practice procedures. That is, working memory studies are predicted to yield exceptionally large PH (0.83 for Simple Manipulation and 0.85 for CE Demand) and VS (1.83 for Simple Manipulation and 1.47 for CE Demand) effect sizes when best practice procedures are employed. Further, although overlap estimates in PH performance (48.4-52.4%) are consistent with arguments that suggest approximately 50% of children with ADHD do not exhibit working memory deficits, 70.8%-77.4% of visuospatial performance is not expected to overlap between ADHD and TD groups, and 92-96% of children with ADHD are predicted to score below the VS mean of typically developing children. Collectively, these findings suggest that the combination of best case procedures with visuospatial tasks are expected to result in exceptionally large magnitude between-group differences, and provide strong evidence that working memory is a core deficit of ADHD.

The current study updated previous meta-analytic reviews (Martinussen et al., 2005; Willcutt et al., 2005) by including 42 new studies and was the first meta-analysis to examine previously unexamined moderators of WM deficits in children with ADHD compared to typically developing children. A few potential limitations, however, warrant consideration. For instance, several of the studies did not specify which subtypes of ADHD (e.g. Inattentive, Hyperactive/Impulsive, Combined) were included in their study. If the included studies specified a subtype, ADHD-Combined group was included in the current analyses. Choosing the combined subtype, however, may not have created a large difference in our results, since extant literature indicates that current diagnostic criteria for ADHD subtypes may not be the most valid method of grouping children (Jensen, Martin, & Cantwell, 1997), as some children may meet criteria for different subtypes throughout their childhood (Lahey, Pelham, Loney, Lee, & Willcutt, 2005), and extant literature reveals that children diagnosed with different subtypes perform similarly on working memory tasks (Mayes, Calhoun, Chase, Mink, & Stagg, 2009). Another potential confound is that there may be other moderating variables that we did not include, as indicated by the significant residual in all four of the regression equations. Future studies may incorporate additional moderating variables in their analyses to discern variables that significantly affect the relationship between children with ADHD and working memory deficits.

The current study sought to elucidate working memory differences in children with ADHD compared to their typically developing peers. Analyses revealed that several methodological and experimental variables yielded significant between-group differences, such that children with ADHD performed worse than the typically developing group. Previous studies that have found small or nonsignificant differences in working memory performance may have employed task, diagnostic, and participants variables that do not optimize detection of between-group effects. Findings from the current meta-analytic review provides further evidence that working memory is a core deficit of ADHD that appears to be present in most children with the disorder. Current intervention strategies that target secondary symptoms of the disorder (e.g., inattention, hyperactivity) are typically only effective in the short-term (Jensen et al., 2001). Future treatments that target working memory may not only improve working memory abilities, but effectively improve symptoms that are secondary to working memory deficits (e.g., inattention, hyperactivity), and may provide long-term treatment gains.

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Table 1. Working Memory Studies of Between-Group Comparisons of ADHD and Typically Developing Children

| Citation | N | Percent Female | Mean Ages (SD) | Diagnostic Method | Trial # | Measure | Response Modality | Performance Metric | Simple Manipulation | CE Demand | PH/VS | Results |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Chelune et al., (1986) | 24 ADHD<br>24 TD | 29.17<br>29.17 | 9.38(NR)<br>9.38(NR) | Simple | 2 | K-ABC: Number Recall | Recall | Trial | No | No | PH | ADHD < TD** |
| Breen (1989), Cond. 1 | 13 ADHD<br>13 TD | 100<br>100 | NR<br>NR | Simple | 3 | K-ABC: Number Recall | Recall | Trial | No | No | PH | ADHD < TD |
| Breen (1989), Cond. 2 | 13 ADHD<br>13 TD | 100<br>100 | NR<br>NR | Simple | 2-4 | K-ABC: Spatial Memory | Recall | Trial | No | No | VS | ADHD < TD |
| Gorenstein et al., (1989) | 21 ADHD<br>26 TD | 4.76<br>57.69 | 10.07 (1.23)<br>10.18 (1.13) | Simple | 35 | Sequential Memory Task | Recognition | Trial | Yes | Yes | VS | ADHD > TD†* |
| Shue & Douglas (1992), Cond. 1 | 22 ADHD<br>18 TD | 13.64<br>11.11 | 10.30 (1.57)<br>10.31 (1.54) | Comprehensive | 2 | WMS: Digits Backward | Recall | Trial | Yes | No | PH | ADHD < TD |
| Shue & Douglas (1992), Cond. 2 | 22 ADHD<br>18 ADHD | 13.64<br>11.11 | 10.30 (1.57)<br>10.31 (1.54) | Comprehensive | 1 | Spatial Locations Task | Recall | Stimuli | No | No | VS | ADHD < TD† |
| Kaplan et al., (1998), Cond. 1 | 53 ADHD<br>112 TD | 13.21<br>26.79 | 12.37 (2.37)<br>11.27 (2.21) | Simple | 1 | WRAML: Number/Letter | Recall | Trial | No | No | PH | ADHD < TD* |
| Kaplan et al., (1998), Cond. 2 | 53 ADHD<br>112 TD | 13.21<br>26.79 | 12.37 (2.37)<br>11.27 (2.21) | Simple | 4 | WRAML: Picture Memory | Recall | Trial | Yes | Yes | VS | ADHD > TD* |
| Karatekin & Asarnow (1998), Cond. 1 | 30 ADHD<br>26 TD | 38.71<br>55.56 | 13.75 (3.14)<br>13.04 (2.5) | Simple | 2 | DS Backward | Recall | Trial | Yes | No | PH | ADHD < TD |
| Karatekin & Asarnow (1998), Cond. 2 | 31 ADHD<br>27 TD | 38.71<br>55.56 | 13.75 (3.14)<br>13.04 (2.50) | Simple | 14 | Dot Test | Recall | Trial | No | No | VS | ADHD > TD†* |
| Loe et al., (1999) | 26 ADHD<br>33 TD | 48.48<br>38.46 | 10.20 (1.60)<br>10.40 (1.70) | Comprehensive | 32 | Memory-Guided Saccade | Recall | Trial | No | No | VS | ADHD < TD†** |
| Norrelgen et al., (1999) | 9 ADHD<br>19 TD | 0<br>0 | 11.17(NR)<br>11.52(NR) | Simple | 4 | Memory Test: 5 syllables | Recall | Stimuli | No | No | PH | ADHD < TD |
| Cornoldi et al., (2001), Cond. 1 | 22 ADHD<br>22 TD | 22.72<br>22.72 | 9.40 (1.10)<br>9.20 (1.10) | Comprehensive | 2 | Recall of final word | Recall | Stimuli | No | No | PH | ADHD < TD*** |
| Cornoldi et al., (2001), Cond. 2 | 34 ADHD<br>50 TD | 26.47<br>28.00 | 9.26 (1.39)<br>9.18 (1.35) | Comprehensive | 6 | VSWM Selective Span Task | Recall | Stimuli | No | No | VS | ADHD < TD** |

| Citation | N | Percent Female | Mean Ages (SD) | Diagnostic Method | Trial # | Measure | Response Modality | Performance Metric | Simple Manipulation | CE Demand | PH/VS | Results |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Willcutt et al., (2001)[a] | 35 ADHD<br>84 TD | NR<br>NR | 10.80 (2.20)<br>10.70 (2.20) | Comprehensive | 2-6 | Counting Span | Recall | Trial | Yes | Yes | PH | ADHD < TD |
| Siklos & Kerns (2001) | 19 ADHD<br>19 TD | 10.53<br>10.53 | 10.07 (2.12)<br>10.04 (1.72) | Comprehensive | 305 | CHIPASAT | Recall | Stimuli | Yes | Yes | PH | ADHD < TD** |
| McInnes et al., (2002), Cond. 1 | 21 ADHD<br>19 TD | 0<br>0 | 10.90 (1.20)<br>10.80 (0.80) | Simple | 2 | CMS: DS Backward | Recall | Trial | Yes | No | PH | ADHD < TD*** |
| McInnes et al., (2002), Cond. 2 | 21 ADHD<br>19 TD | 0<br>0 | 10.90 (1.20)<br>10.80 (0.80) | Simple | 1 | WRAML: Finger Windows Backward | Recall | Trial | Yes | No | VS | ADHD < TD*** |
| Rucklidge & Tannock (2002) | 35 ADHD<br>37 TD | 42.86<br>51.35 | 15.18 (1.36)<br>14.95 (1.10) | Comprehensive | 2 | WISC-III: DS Backward | Recall | Trial | Yes | No | PH | ADHD < TD |
| Schmitz et al., (2002) | 10 ADHD<br>60 TD | 30<br>65 | 14.10 (1.40)<br>13.80 (1.00) | Comprehensive | 2 | Digit Span | Recall | Trial | No | No | PH | ADHD < TD*** |
| Karatekin (2004), Cond. 1 | 24 ADHD<br>27 TD | 4.00<br>14.81 | 11.41 (1.88)<br>11.08 (1.82) | Comprehensive | 16 | Verbal Working Memory Task | Recognition | Stimuli | Yes | No | PH | ADHD < TD |
| Karatekin (2004), Cond. 2 | 24 ADHD<br>27 TD | 4.00<br>14.81 | 11.41 (1.88)<br>11.08 (1.82) | Comprehensive | 16 | Spatial Working Memory Task | Recognition | Stimuli | No | No | VS | ADHD < TD |
| Westerberg et al., (2004) | 27 ADHD<br>53 TD | 0<br>0 | 11.40 (2.20)<br>11.40 (2.00) | Simple | 2 | Visuospatial WM Task | Recall | Stimuli | No | No | VS | ADHD < TD** |
| Scheres et al., (2004) | 23 ADHD<br>22 TD | 0<br>0 | 8.10 (1.70)<br>9.60 (1.80) | Comprehensive | 4 | SOPT | Recognition | Stimuli | No | No | VS | ADHD > TD† |
| Jonsdottir et al., (2005), Cond. 1 | 15 ADHD<br>15 TD | 26.67<br>40.00 | 10.67(1.29)<br>10.33 (1.29) | Comprehensive | 2 | K-ABC: Number Recall | Recall | Trial | No | No | PH | ADHD < TD |
| Jonsdottir et al., (2005), Cond. 2 | 15 ADHD<br>15 TD | 26.67<br>40.00 | 10.67 (1.29)<br>10.33 (1.29) | Comprehensive | 2-4 | K-ABC: Spatial Memory | Recall | Trial | No | No | VS | ADHD < TD |
| McInerney et al., (2005), Cond. 1 | 30 ADHD<br>30 TD | 10.00<br>10.00 | 10.80 (1.97)<br>10.12 (1.87) | Comprehensive | 305 | CHIPASAT | Recall | Stimuli | Yes | Yes | PH | ADHD < TD** |
| McInerney et al., (2005), Cond. 2 | 30 ADHD<br>30 TD | 10.00<br>10.00 | 10.80 (1.97)<br>10.12 (1.87) | Comprehensive | 2 | Children's Size Ordering Task | Recall | Trial | Yes | Yes | VS | ADHD < TD** |
| Passolunghi et al., (2005) | 10 ADHD<br>10 TD | NR<br>NR | 9.80 (0.48)<br>9.85 (0.49) | Comprehensive | 2 | WAIS-R: DS Backward | Recall | Trial | Yes | No | PH | ADHD < TD* |
| Goldberg et al., (2005) | 21 ADHD<br>32 TD | 9.52<br>34.38 | 9.80 (1.30)<br>10.40 (1.50) | Comprehensive | 4 | CANTAB: Spatial WM | Recognition | N/A | No | No | VS | ADHD > TD†* |
| Healey & Rucklidge (2006) | 29 ADHD<br>30 TD | 27.58<br>56.67 | 11.44 (0.85)<br>11.10 (0.89) | Comprehensive | 2 | WISC-III: DS Backward (Raw Score) | Recall | Trial | Yes | No | PH | ADHD < TD |

| Citation | N | Percent Female | Mean Ages (SD) | Diagnostic Method | Trial # | Measure | Response Modality | Performance Metric | Simple Manipulation | CE Demand | PH/VS | Results |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Rosenthal et al., (2006) | 28 ADHD<br>27 TD | 21.43<br>55.55 | 11.44 (2.11)<br>11.49 (2.21) | Simple | 2 | DS Backward: Longest Span (Raw Score) | Recall | Trial | Yes | No | PH | ADHD < TD |
| Happe et al., (2006) | 29 ADHD<br>31 TD | 0<br>0 | 11.60 (1.70)<br>11.20 (2.00) | Simple | 4 | CANTAB: Spatial WM | Recognition | N/A | No | No | VS | ADHD > TD†*** |
| Manassis et al., (2007), Cond. 1 | 21 ADHD<br>35 TD | 19.00<br>37.00 | 9.60 (1.43)<br>9.71 (1.32) | Comprehensive | 305 | CHIPASAT | Recall | Stimuli | Yes | Yes | PH | ADHD < TD*** |
| Manassis et al., (2007), Cond. 2 | 21 ADHD<br>35 TD | 19.00<br>37.00 | 9.60 (1.43)<br>9.71 (1.32) | Comprehensive | 1 | WRAML: Finger Windows-Backward | Recall | Trial | Yes | No | VS | ADHD < TD** |
| Pasini et al., (2007), Cond. 1 | 50 ADHD<br>44 TD | 0<br>0 | 10.50 (1.78)<br>10.63 (2.06) | Comprehensive | 20 | N-Back WM Test: Phonological | Recognition | Stimuli | No | No | PH | ADHD < TD |
| Pasini et al., (2007), Cond. 2 | 50 ADHD<br>44 TD | 0<br>0 | 10.50 (1.78)<br>10.63 (2.06) | Comprehensive | 20 | N-Back WM Test: Spatial | Recognition | Stimuli | No | No | VS | ADHD < TD* |
| Yang et al., (2007), Cond. 1 | 40 ADHD<br>40 TD | 20.00<br>15.00 | 8.46 (1.63)<br>8.63 (1.37) | Simple | 2 | DS Backward | Recall | Trial | Yes | No | PH | ADHD < TD** |
| Yang et al., (2007), Cond. 2 | 40 ADHD<br>40 TD | 20.00<br>15.00 | 8.46 (1.63)<br>8.63 (1.37) | Simple | 2 or 3 | Corsi Block Task | Recall | Trial | No | No | VS | ADHD < TD*** |
| Drechsler et al., (2008) | 23 ADHD<br>24 TD | 8.70<br>4.17 | 12.20 (0.80)<br>11.90 (0.60) | Comprehensive | 75 | 2-back | Recognition | Trial | Yes | Yes | PH | ADHD < TD |
| Kobel et al., (2008) | 14 ADHD<br>12 TD | 0<br>0 | 10.43 (1.34)<br>10.92 (1.62) | Comprehensive | 40 | 2-back | Recognition | Trial | Yes | Yes | PH | ADHD < TD** |
| Rapport et al., (2008), Cond. 1 | 12 ADHD<br>11 TD | 0<br>0 | 8.75 (1.29)<br>9.36 (1.43) | Comprehensive | 24 | Phonological Task (Number-Letter) | Recall | Stimuli | Yes | Yes | PH | ADHD < TD*** |
| Rapport et al., (2008), Cond. 2 | 12 ADHD<br>11 TD | 0<br>0 | 8.75 (1.29)<br>9.36 (1.43) | Comprehensive | 24 | Visuospatial Task (Dot in the Box) | Recall | Stimuli | Yes | Yes | VS | ADHD < TD*** |
| Skowronek et al., (2008), Cond. 1 | 12 ADHD<br>17 TD | 0<br>0 | 12.20 (1.48)<br>11.50 (1.59) | Simple | 2 | DS Backward | Recall | Trial | Yes | No | PH | ADHD < TD** |
| Skowronek et al., (2008), Cond. 2 | 12 ADHD<br>17 TD | 0<br>0 | 12.20 (1.48)<br>11.50 (1.59) | Simple | 1 | Simon Task | Recall | Trial | No | No | VS | ADHD < TD* |
| Tiffin-Richards et al., (2008)[a] | 20 ADHD<br>19 TD | 10.00<br>30.00 | 11.60 (1.30)<br>11.70 (1.30) | Simple | 2 | DS Backward | Recall | Trial | Yes | No | PH | ADHD < TD |
| Gau et al., (2009), Cond. 1 | 53 ADHD<br>53 TD | 24.50<br>24.50 | 12.70 (1.40)<br>12.70 (1.20) | Comprehensive | 2 | DS Backward | Recall | Stimuli | Yes | No | PH | ADHD < TD |
| Gau et al., (2009), Cond. 2 | 53 ADHD<br>53 TD | 24.50<br>24.50 | 12.70 (1.40)<br>12.70 (1.20) | Comprehensive | 1 to 3 | CANTAB: Spatial Span | Recall | Stimuli | No | No | VS | ADHD < TD |

| Citation | N | Percent Female | Mean Ages (SD) | Diagnostic Method | Trial # | Measure | Response Modality | Performance Metric | Simple Manipulation | CE Demand | PH/VS | Results |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Corbett et al., (2009) | 18 ADHD<br>18 TD | 33.33<br>33.33 | 9.40 (1.98)<br>9.56 (1.81) | Comprehensive | 1 to 3 | CANTAB: Spatial Span | Recall | Stimuli | No | No | VS | ADHD < TD* |
| De Jong et al., (2009)[a] | 24 ADHD<br>26 TD | 14.29<br>38.46 | 9.00 (1.31)<br>9.31 (0.92) | Comprehensive | 2 or 3 | Corsi Block Task | Recall | Trial | No | No | VS | ADHD < TD |
| Mahone et al., (2009) | 60 ADHD<br>60 TD | 40.00<br>48.33 | 10.30 (1.30)<br>10.30 (1.30 | Comprehensive | Variable (≥72) | Memory Guided Saccades | Recall | Trial | No | No | VS | ADHD < TD |
| Van de Voorde (2009)[a] | 19 ADHD<br>19 TD | 15.79<br>42.11 | 10.60 (1.58)<br>10.04 (1.48) | Comprehensive | 40 | 1-Back Task | Recognition | Trial | No | No | VS | ADHD < TD† |
| Holmes et al., (2010), Cond. 1[a] | 83 ADHD<br>50 TD | 14.46<br>40.00 | 9.75 (1.00)<br>9.83 (1.00) | Simple | 6 | AWMA: Listening Recall | Recall | Trial | Yes | Yes | PH | ADHD < TD |
| Holmes et al., (2010), Cond. 2[a] | 83 ADHD<br>50 TD | 14.46<br>40.00 | 9.75 (1.00)<br>9.83 (1.00) | Simple | 6 | AWMA: Spatial Span | Recall | Trial | Yes | Yes | VS | ADHD < TD |
| Huang-Pollock & Karalunas (2010) | 32 ADHD<br>48 TD | 31.25<br>64.58 | 10.42 (1.47)<br>10.48 (1.08) | Comprehensive | 288 | Alphabet Arithmetic | Recall | Trial | Yes | Yes | PH | ADHD < TD* |
| Marx et al., (2010) | 21 ADHD<br>20 TD | 0<br>0 | 9.75 (1.84)<br>9.76 (1.59) | Comprehensive | 60 | 2-Back Task | Recognition | Trial | Yes | Yes | PH | ADHD < TD |
| Alderson et al., (2010), Cond. 1 | 14 ADHD<br>13 TD | 0<br>0 | 9.27 (1.09)<br>10.29 (1.53) | Comprehensive | 24 | Phonological Task (Number-Letter) | Recall | Stimuli | Yes | Yes | PH | ADHD < TD*** |
| Alderson et al., (2010), Cond. 2 | 14 ADHD<br>13 TD | 0<br>0 | 9.27 (1.09<br>10.29 (1.53) | Comprehensive | 24 | Visuospatial Task (Dot in the Box) | Recall | Stimuli | Yes | Yes | VS | ADHD < TD*** |
| Zinke et al., (2010) | 22 ADHD<br>39 TD | 18.18<br>35.90 | 9.80 (0.89)<br>9.73 (0.74) | Comprehensive | 24 | 1-Back (Pictures) | Recognition | Trial | No | No | VS | ADHD < TD |

*Note.* All studies were between-groups comparisons of ADHD and typically developing children. Number of females reported as percentage. ADHD = attention-deficit/hyperactivity disorder; AWMA = Automated Working Memory Assessment; CANTAB = Cambridge Neuropsychological Test Automated Battery; CHIPASAT = Children's Paced Auditory Serial Addition Task; CMS = Children's Memory Scales; Comprehensive = Semistructured or structured interview; DS = digit span; K-ABC = Kaufman Assessment Battery for Children; N/A = Not Applicable; NR = Not Reported; PH = phonological; ROCF = Rey-Osterrieth Complex Figure; SOPT = Self-Ordered Pointing Task; STM = short-term memory; SWM = spatial working memory; TD = typically developing; VADS = visual aural digit span test; VS = visuospatial; VSWM = Visuospatial Working Memory; WAIS = Wechsler Adult Intelligence Scale; WISC = Wechsler Intelligence Scale for Children; WM = working memory; WMS = Wechsler Memory Scales; WRAML = Wide Range Assessment of Memory and Learning; † = dependent measure is number of errors

[a] Study did not report *p* values that compared ADHD vs. TD for WM performance.

* = $p < .05$; ** = $p < .01$; *** = $p < .001$

Table 2. Weighted Regression Model and Moderating Variables for PH and VS

| | PH-Simple Manipulation | | | PH-CE Demand | | | VS-Simple Manipulation | | | VS-CE Demand | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *Q* | *df* | *p* | *Q* | *df* | *p* | *Q* | *df* | *p* | *Q* | *df* | *p* |
| Regression | 17.95 | 7 | <.001 | 17.62 | 7 | < .001 | 39.54 | 7 | < .001 | 43.13 | 7 | < .001 |
| Residual | 31.42 | 18 | <.001 | 31.74 | 18 | <.001 | 99.53 | 15 | < .001 | 95.94 | 15 | < .001 |
| $R^2$ | 0.363 | | | 0.357 | | | 0.284 | | | 0.310 | | |
| Adjusted $R^2$ | 0.116 | | | 0.107 | | | -0.05 | | | -0.01 | | |
| Constant | 2.68 | | | 2.46 | | | 1.04 | | | 0.98 | | |

| Moderator Variables | *B* | *SEB* | *z* | *p* | *B* | *SEB* | *z* | *p* | *B* | *SEB* | *z* | *p* | *B* | *SEB* | *z* | *p* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Percent Female | 0.004 | 0.007 | 0.76 | ns | 0.003 | 0.007 | 0.57 | ns | -0.009 | 0.019 | -1.22 | <.001 | -0.012 | 0.017 | -1.79 | <.05 |
| Age | -0.154 | 0.078 | -2.61 | <.001 | -0.136 | 0.066 | -2.74 | < .001 | -0.102 | 0.115 | -2.28 | <.01 | -0.104 | 0.112 | -2.35 | <.001 |
| Diagnostic Method | -0.197 | 0.189 | -1.38 | ns | -0.164 | 0.178 | -1.22 | ns | -0.382 | 0.413 | -2.38 | <.001 | -0.314 | 0.413 | -1.92 | < .05 |
| Trials Per Set Size | -0.003 | 0.326 | -0.01 | ns | 0.185 | 0.756 | 0.33 | ns | 0.526 | 0.515 | 2.63 | <.001 | 0.551 | 0.5 | 2.79 | <.01 |
| Response Modality | -0.5 | 0.377 | -1.75 | <.05 | -0.42 | 0.367 | -1.52 | ns | 0.627 | 0.731 | 2.20 | <.05 | 0.749 | 0.703 | 2.69 | <.01 |
| Performance Metric | 0.098 | 0.177 | 0.73 | ns | 0.049 | 0.154 | 0.42 | ns | 0.366 | 0.328 | 2.87 | <.001 | 0.347 | 0.3 | 2.93 | <.01 |
| Simple Manipulation | 0.094 | 0.205 | 0.61 | ns | — | — | — | — | 0.166 | 0.4 | 1.07 | ns | — | — | — | — |
| CE Demand | — | — | — | — | -0.11 | 0.703 | -0.21 | ns | — | — | — | — | 0.412 | 0.48 | 2.17 | <.01 |

Note. *B* = regression coefficients; CE = Central Executive; *df* = degrees of freedom; PH = Phonological; *Q* = chi-square value; $R^2$ = variance accounted for by the model; *SEB* = standard error of the regression coefficients; VS = Visuospatial; and *z* = z-value.

Table 3. Best case estimation and predicted overlap of ADHD and TD groups' WM performance

| Variable Included | Effect Size | % Nonoverlap | % Overlap | Overlap Statistic[a] | % ADHD < TD[b] |
|---|---|---|---|---|---|
| Manipulation | | | | | |
| PH Studies | 0.85 | 51.6 | 48.4 | 0.74 | 82 |
| VS Studies | 1.47 | 70.7 | 29.3 | 0.84 | 92 |
| Working Memory | | | | | |
| PH Studies | 0.83 | 47.4 | 52.6 | 0.71 | 79 |
| VS Studies | 1.83 | 77.4 | 22.6 | 0.9 | 96 |

*Note.* ADHD = attention-deficit/hyperactivity disorder; PH = phonological; TD = typically developing; VS = visuospatial; WM = working memory

[a] Probability of a randomly selected participant in the ADHD group performing lower than a randomly selected participant in the TD group.

[b] Percentage of the ADHD group that would fall below average in the TD group.

# VITA

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Extant literature has demonstrated equivocal results regarding whether working memory is a core deficit of Attention-Deficit/Hyperactivity Disorder. Failure to find uniform working memory deficits in children with ADHD, relative to typically developing children, may reflect methodological and experimental variables that suppressed between-group effects. The current study employed meta-analytic techniques to examine a broad range of moderating variables of effect size variability across working memory performance. Results revealed moderate overall phonological and visuospatial working memory effect sizes. In addition, several moderating variables explained significant effect size variability across studies, while examination of best case estimation procedures and percent overlap lend further support for working memory as a core deficit of the disorder.

ADVISER'S APPROVAL: R. Matt Alderson, Ph.D.