Working memory and symptoms of attention deficit hyperactivity disorder in children

Alison Margaret Colbert

Follow this and additional works at: http://commons.emich.edu/theses

Part of the Clinical Psychology Commons

Recommended Citation
Colbert, Alison Margaret, "Working memory and symptoms of attention deficit hyperactivity disorder in children" (2015). Master's Theses and Doctoral Dissertations. 730.
http://commons.emich.edu/theses/730
Working Memory and Symptoms of Attention Deficit Hyperactivity Disorder in Children

by

Alison M. Colbert, M.A.

Dissertation

Submitted to the Department of Psychology

Eastern Michigan University

in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Clinical Psychology

Dissertation Committee:

Jin Bo, Ph.D., Chair
Renee Lajiness-O’Neill, Ph.D.
Karen Saules, Ph.D.
Walter Harrell, Ph.D.

May 5, 2015

Ypsilanti, Michigan
Acknowledgements

I am deeply grateful to the families who participated in this study. It is my hope that this project leads to further research that promotes positive change in the diagnosis and treatment of neurodevelopmental disorders.

I would also like to express my sincere thanks to my advisor and chair, Dr. Jin Bo. Throughout this project, she was incredibly encouraging, and she provided feedback that both challenged and advanced the project. I could not have hoped for a more supportive, kind mentor.

I would also like to acknowledge my committee members from Eastern Michigan University, Dr. Renee Lajiness-O’Neill and Dr. Karen Saules, who continually encouraged my efforts. My external committee member, Dr. Walter Harrell, was also a source of strong support, and I am grateful for his participation in this project.

I am grateful to the Blue Cross Blue Shield Michigan Foundation Student Award Program for financially supporting this project.

Finally, I would like to thank my family, friends, and peers. The constant encouragement and support of the people around me is invaluable. In particular, I am grateful to my parents, Joy Bolger and Doug Hoover, who have always stood strongly behind me. To my brother, Brock Hoover, I am grateful for challenging me to always be better. To my husband, Vincent Colbert, I am thankful for his support during the long days, nights, weeks, months, and years that I have spent on this endeavor. I am blessed by the people who surround me.
Abstract

Attention Deficit Hyperactivity Disorder (ADHD) is a disorder mainly characterized by high levels of inattention, hyperactivity, and impulsiveness. Although ADHD is a topic of great interest in multiple domains, much remains to be explored before a thorough understanding will be possible. Recently, working memory (WM) has gained attention as a potential core deficit of ADHD. Therefore, theories of ADHD and WM may provide guidance for increased understanding of ADHD, and continued research on ADHD, guided by WM theory, will maximize the effectiveness of assessment and treatment for this disorder. The current study utilized a model integrating WM measurement and symptoms of ADHD. To investigate the relationship between continuous measurement of ADHD symptoms and WM functioning, experimental paradigms and clinical assessment of WM capacity were utilized. Results indicated computerized change-detection tasks are not effectively eliciting WM in children, as capacity was significantly lower than that of adults. A trend for developmental increase in WM was found. The WISC-IV Arithmetic subtest was the subtest most consistently related to other clinical and experimental WM measures. The Arithmetic and Digit Span Backward subtests were most consistently related to ADHD inattentive symptoms though significant variance was still unaccounted for, and no WM measure was consistently related to ADHD hyperactive/impulsive symptoms. Overall, continuous measurement of ADHD inattentive symptoms best characterized relationships between ADHD and WM functioning, and WM did not have utility in categorical classification of ADHD. Results highlight the need for advancement in WM measurement, as well as the utility of continuous characterization of disorders.
# Table of Contents

Chapter 1: Introduction.................................................................................................................. 1

Chapter 2: Classification, Etiology and Theories of ADHD......................................................... 4

  ADHD Classification...................................................................................................................... 4
  DSM ............................................................................................................................................... 4
  ICD-10 Hyperkinetic Disorder (HKD).......................................................................................... 5

ADHD Etiology................................................................................................................................. 6

  Heritability....................................................................................................................................... 6

  Structural and functional neuroimaging and ADHD symptoms ............................................. 7

Cognitive Models of ADHD ........................................................................................................... 10

  Behavioral inhibition models ....................................................................................................... 10
  Rapport’s Functional Working Memory Model........................................................................... 12
    WM, ADHD symptoms, and brain function. ............................................................................. 16

Chapter 3: Measurement of ADHD and WM.............................................................................. 19

Subjective Data.............................................................................................................................. 19

  Clinical interview......................................................................................................................... 19
  Rating scales................................................................................................................................ 26

Neuropsychological Assessment.................................................................................................. 27

  WM assessment............................................................................................................................ 28
    Span tasks................................................................................................................................... 30
    Computerized assessment measures......................................................................................... 36
    Cognitive subtests....................................................................................................................... 38
    Rating scales............................................................................................................................... 40
Chapter 4: Rationale for the Present Study ................................................................. 44
  WM Construct and Measurement........................................................................ 44
  ADHD Classification............................................................................................ 46
    Continuous versus categorical classification.................................................. 46
    ADHD subtypes.................................................................................................. 48
    Additional variables......................................................................................... 50
  Model for the Present Study............................................................................. 51
Chapter 5: Aims and Hypotheses ........................................................................ 52
  Aims of the Current Study.................................................................................. 52
  Hypotheses......................................................................................................... 52
    Validation of computerized change-detection paradigms in children............ 52
    Clinical versus experimental WM measurement........................................... 53
    WM and ADHD symptoms.............................................................................. 53
    Classification of ADHD via the WMI and change-detection tasks................. 54
Chapter 6: Method.................................................................................................. 55
  General Procedure.............................................................................................. 55
  Measures............................................................................................................ 55
    Computerized change-detection tasks............................................................ 55
    Computerized complex span task.................................................................... 57
    WISC-IV........................................................................................................... 58
    WASI-2............................................................................................................ 58
    CTOPP-2 ......................................................................................................... 59
    Conners 3-P .................................................................................................... 59
Revised Children’s Manifest Anxiety Scale, Second Edition (RCMAS-2)........60

Adult self-report measures ..............................................................................61

Beck Anxiety Inventory (BAI)........................................................................61

Beck Depression Inventory (BDI).................................................................61

Conners Adult ADHD Rating Scale..............................................................61

Data Analysis....................................................................................................61

Chapter 7: Results.............................................................................................63

Participants.......................................................................................................63

Preliminary data analyses.................................................................................68

Normality of distribution..................................................................................69

Descriptive statistics of child sample ............................................................73

Intelligence .......................................................................................................76

Working memory..............................................................................................76

Phonological awareness...................................................................................76

ADHD symptoms .............................................................................................77

Other psychological/behavioral symptoms ....................................................77

Descriptive statistics of adult sample .............................................................78

Correlations among child WM measures, ADHD symptoms, and other
neuropsychological variables ........................................................................78

Analyses of Primary Study Hypotheses .........................................................81

Aim 1 ...............................................................................................................81

Hypothesis 1 ...................................................................................................81

Hypothesis 2 ...................................................................................................82
Aim 4: WM and ADHD classification ........................................ 112
Continuous ADHD symptoms ............................................. 112
Categorical ADHD diagnosis ............................................. 114
Limitations ............................................................................. 114
Future Directions and Implications ....................................... 116
References ............................................................................ 120
Appendix A ........................................................................... 145
Appendix B ........................................................................... 147
Appendix C ........................................................................... 148
Appendix D ........................................................................... 149
Appendix E ........................................................................... 152
List of Tables

Table 1: Assessment Measures Relevant to ADHD Diagnosis ........................................20
Table 2: Working Memory Assessment Measures and their Association with ADHD .......32
Table 3: Child Participant Demographic Characteristics ..................................................64
Table 4: Adult Participant Demographic Characteristics ..................................................79
Table 5: Normality of Distribution for All Child Measures ................................................71
Table 6: Normality of Distribution for All Adult Measures ..............................................72
Table 7: Descriptives of Standardized Child Assessment Measures ..................................73
Table 8: Descriptives of Standardized Adult Assessment Measures .................................78
Table 9: Correlations Among Child WM Measures, ADHD Symptoms, and Other Neuropsychological Variables ..........................................................80
Table 10: Correlations Among Clinical WM Measures ...................................................84
Table 11: Correlations Between Clinical and Experimental WM Measures ....................85
Table 12: Simple and Stepwise Regression Analyses Predicting Change-Detection VSWM ........................................................................................................86
Table 13: Simple and Stepwise Multiple Regression Analyses Predicting AWMA-2 VWM ..........................................................87
Table 14: Simple and Stepwise Multiple Regression Analyses Predicting AWMA-2 VSWM ........................................................................................................88
Table 15: Correlations Among WISC-IV WM Measures and ADHD Symptoms ...........91
Table 16: Correlations Among Computerized Change-Detection Tasks and ADHD Symptoms ........................................................................................................92
Table 17: Correlations Among AWMA-2 WM Measures and ADHD Symptoms ............93
Table 18: Simple and Stepwise Multiple Regression Analyses Predicting WMI Performance .......................................................... 95

Table 19: Simple and Stepwise Multiple Regression Analyses Predicting Arithmetic Performance .......................................................... 96

Table 20: Simple and Stepwise Multiple Regression Analyses Predicting ADHD Symptoms with WISC-IV WM Tasks ............................................................................. 99
List of Figures

Figure 1. The Revised Model of WM (Baddeley, 2000) ................................................................. 13

Figure 2. The Functional WM Model of ADHD ................................................................. 15

Figure 3. Example of VSWM Change-Detection Task .................................................... 56

Figure 4. Example of VWM Change-Detection Task ...................................................... 57

Figure 5. Example of AWMA WM Screening Tasks ....................................................... 58

Figure 6. VSWM and VWM Mean Performance Across Elements ................................ 82

Figure 7. VSWM and VWM Capacity as a Function of Age ............................................ 83
Chapter 1: Introduction

Attention Deficit Hyperactivity Disorder (ADHD) is a neurodevelopmental disorder characterized by high levels of inattention, hyperactivity, and impulsiveness in children. It is in many ways an exaggeration of normal behavior, and children with ADHD may exhibit either too much or not enough of what is expected in a given setting (Goldstein & Naglieri, 2008). While widely agreed upon that ADHD is a valid and impairing disorder (Barkley et al., 2002), the delineation between normal behavior and pathological variation, along with the underlying cause, is still controversial (American Academy of Child and Adolescent Psychiatry [AACP], 2007; Wolraich, 1999).

Recent reports suggest 5% of school-age children meet criteria for ADHD [the Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition (DSM-5 APA, 2013)]. However, large discrepancies in prevalence estimates exist, and it is important to note that methodological differences between studies play an important role in explaining variability in ADHD prevalence (Polanczyk, de Lima, Horta, Biederman, & Rohde, 2007). Surveys in community samples suggest a prevalence of 1.7% to 16% (Goldman, Genel, Bexman, & Slanetz, 1998), though the prevalence of ADHD in clinical settings is much higher. Cantwell (1996) reported children with ADHD comprise up to 50% of some childhood psychiatric populations, and ADHD accounts for 10% of behavioral problems seen in general pediatric settings. Thus, it is not surprising that ADHD places a high psychosocial burden on families and children due to a wide range of reasons, such as decreased quality of life, increased educational demands and behavioral problems, and complicating comorbid conditions (Cuffe, Moore, & McKeown, 2005). Pelham, Foster, and Robb (2007) estimate ADHD costs society between $36 and $53.4 billion annually.
As ADHD has been increasingly conceptualized as a neurodevelopmental disorder, models have been developed to explain the associated cognitive and behavioral symptoms. Specifically, these models seek to identify key domains of cognitive functioning in order to establish endophenotypes, constructs that define measurable components and provide a bridge between the clinical expression or phenotype and underlying causes of neuropsychiatric diseases (Gottesman & Gould, 2003). Endophenotypes can be neurophysiological, biochemical, endocrinological, neuroanatomical, cognitive, or neuropsychological in nature (Gottesman & Gould, 2003).

Endophenotypes may be useful in ADHD research because they could lead to more objective neurocognitive diagnostic procedures and greater predictive power (Crosbie, Pé-russe, Barr, & Schachar, 2008), as well as identification of the core features of the disorder (Gottesman & Gould, 2003). Endophenotypes may also offer a fundamental framework for evaluating and developing intervention strategies. For example, interventions that target core psychological-cognitive features of ADHD could produce the greater level and breadth of therapeutic change (Rapport, Chung, Shore, & Isaacs, 2001) than methods targeting peripheral features. However, it is also notable that endophenotypes in behavioral research do not necessarily add to understanding of disease pathogenesis. In order for endophenotypes to be useful, their relationship to biological processes underlying disease must be testable (Bearden & Fremier, 2006). A variety of criteria have been proposed for evaluating the validity and utility of endophenotypes. Among these are: reliable measurement, evidence of heritability, stability over time, familial overlap with the disorder, and common genetic influence underlying endophenotype and disorder (Bearden & Fremier, 2006).
Recently, working memory (WM) has gained attention as an endophenotype of ADHD (e.g., Rapport et al., 2008), and some suggest WM is a core deficit of ADHD (Rapport et al., 2009). Specifically, converging evidence reveals WM deficits occur upstream of phenotypic features like hyperactivity, impulsivity, and inattention (Rapport et al., 2001). Therefore, evaluation of WM in ADHD may lead to advances in diagnosis, treatment, and outcomes, as well as a better understanding of ADHD subtypes. However, though there are a variety of methods available for WM measurement, there is no “gold standard” measure for assessment of WM in children, and no single approach is guaranteed to engage the neural circuitry of WM (Jarrold & Touse, 2006). Therefore, one of the difficulties with conceptualizing WM as an endophenotype for ADHD is problem with measurement reliability among different measurement methods.

In order to better understand the neurocognitive underpinnings of ADHD, the current study will seek to evaluate the relationship between ADHD symptoms and WM functioning. The clinical measurement of WM in children will also be compared to paradigms commonly used in cognitive and experimental research in order to evaluate similarity of constructs being measured, as well as provide suggestions for potential adaptation of current paradigms. The following review will examine models of ADHD, explicate current methods for evaluating ADHD and WM, and present a model for effectively evaluating ADHD, with an emphasis on WM assessment and the relationship between WM functioning and ADHD symptoms.
Chapter 2: Classification, Etiology and Theories of ADHD

ADHD Classification

Currently, the ICD-10 and DSM both offer diagnostic classification for pathological variations from normal behavior in the realms of activity, attention, and impulse control. The ICD-10 (World Health Organization [WHO], 1993) classification describes a narrowly defined syndrome, whereas the DSM-IV-TR and DSM-5 (APA, 2000; APA, 2013) provide broader criteria for diagnosis. Understanding the differences between these systems is critical for conceptualization of ADHD and understanding discrepancies in the field.

**DSM.** DSM-IV-TR conceptualized ADHD as one disorder with three subtypes (inattentive [ADHD-I], hyperactive-impulsive [ADHD-HI], and combined [ADHD-C]), the essential feature being "a persistent pattern of inattention and/or hyperactivity-impulsivity… more frequently displayed and more severe than is typically observed in individuals at a comparable level of development" (p.85, APA, 2000). The predominantly inattentive subtype (ADHD-I) required that six or more symptoms be in the category of inattention. Within this subtype, hyperactivity may still be a clinical feature, though some cases are purely inattentive (APA, 2000). The predominantly hyperactive-impulsive subtype (ADHD-HI) required that six of more symptoms be in the hyperactivity-impulsivity categories, though inattention may still be a clinical feature. The combined subtype (ADHD-C) required six of more symptoms of both inattention and hyperactivity-impulsivity to be present. In order to qualify for diagnosis of any subtype, manifestation of ADHD symptoms must be present in more than one setting. Though the DSM-IV-TR classified ADHD as a disruptive behavior disorder, recent publication of DSM-5 reclassifies it as a neurodevelopmental disorder. DSM-IV-TR criteria...
are discussed in detail here due to their extensive use in the extant research. Changes in
DSM-5 are reflected in Appendix A.

**ICD-10 Hyperkinetic Disorder (HKD).** The ICD-10 criteria for diagnosis of HKD
are stricter than DSM criteria for ADHD with three main differences between the syndromes.
First, according to the ICD-10, HKD is a single disorder marked by symptoms of inattention,
impulsiveness, and hyperactivity (WHO, 1993). Criteria for all three symptom categories
must be met, and ICD-10 criteria do not allow for subtype classification as the DSM-IV-TR
criteria do (see Appendix A). Second, ICD-10 criteria require that individuals meet full crite-
ria for the disorder in two settings (WHO, 1993), rather than simply evidencing impairment
in two situations (APA, 2000). Third, according to the ICD-10, the clinician is encouraged to
diagnose a single, alternative disorder when symptoms of another disorder that may account
for the diagnostic presentation are present (WHO, 1993), whereas multiple co-morbid dia-
gnoses may co-occur with ADHD (APA, 2000). Specifically, DSM provides differential diag-
noses to consider when diagnosing ADHD, and evidence-based, comprehensive assessment
involves determining whether symptoms are attributable to ADHD or another disorder, as
well as consideration of whether one or more comorbid diagnoses are present that are not ex-
plained by a primary diagnosis of ADHD (APA, 2013). Additionally, like the ICD-10, DSM-
5 diagnostic guidelines indicate diagnosis of ADHD should not be made if symptoms are bet-
ter accounted for by another disorder (APA, 2013).

The similarities, differences, strengths and weaknesses of each classification system
have been widely discussed. For example, Lee and colleagues (2008) explored the predictive
validity of ADHD and HKD finding that only 11% of cases that met criteria for ADHD also
met criteria for HKD. While the groups overlapped substantially in terms of important clini-
cal characteristics, the authors noted that ICD-10 criteria may under-identify individuals with substantial impairment (Lee et al., 2008). To sum, although ADHD and HKD are similar syndromes, ADHD represents a broader category than HKD. Alternatively, HKD could be considered a severe subtype of ADHD.

**ADHD Etiology**

The etiology of ADHD is complex, and a combination of factors seems to interact to form a spectrum of neurobiological liability (Curatolo, D’Agati, & Moavero, 2010). Biederman and Spencer (1999) suggest ADHD is “a brain disorder of likely genetic etiology with etiologic and pathophysiological heterogeneity” (pg. 1234). The focus of the proposed study is ADHD and WM; therefore, WM and neurobiological factors will be the focus of the following subsections.

**Heritability.** Heritability is the proportion of phenotypic variance due to genetic factors (Wray & Visscher, 2008). Estimating heritability involves “partitioning observed variation into components that reflect unobserved genetic and environmental factors” (Wray & Visscher, 2008, p. 29). A heritability estimate refers to expected resemblance between relatives and is dependent on assumptions about the underlying environmental and genetic causes of a trait (Wray & Visscher, 2008). Moreover, heritability can change over time due to changes in genetic variance, environmental factors, and the correlation between genes and environment (Wray & Visscher, 2008). Family, twin, and adoption studies provide support for a complex genetic etiology of ADHD (Remschmidt, 2005) and significant heritability (Nigg & Nikolas, 2008). Research shows ADHD occurs more frequently in first-degree biological relatives of children with ADHD than in the general population (APA, 2000). For example, twin studies suggest that heritability is approximately .8 in ADHD (Sagvolden, Jo-
hansen, Aase, & Russell, 2005), though other heritability estimates range from .6 to .9 (Curatolo et al., 2010). Evidence also suggests genetic factors have an influence on dimensional levels of hyperactivity, impulsivity, and inattention (Gjone, Stevenson, & Sundet 1996; Levy, Hay, McStephen, Wood, & Waldman 1997).

Genetic models of ADHD posit that alterations in neurotransmitter systems (Curatolo et al., 2010), especially the dopaminergic and noradrenergic catecholamine systems (Nigg & Nikolas, 2008), contribute to or cause ADHD. Specifically, dopamine transporter, receptor, and precursor genes, as well as noradrenergic receptor genes, have been associated with ADHD symptoms (Nigg & Nikolas, 2008). As the posterior and anterior attention systems operate mainly through noradrenaline and dopamine respectively, (Becker & Schmidt, 2006), Biederman & Spencer (1999) suggest a dysregulation in the catecholamine system may underlie the pathophysiology of ADHD.

**Structural and functional neuroimaging and ADHD symptoms.** ADHD has been increasingly conceptualized as a developmental brain disorder (Seidman, 2006) and is classified as a neurodevelopmental disorder in the DSM-5 (APA, 2013). ADHD symptoms have been linked to irregularity in certain brain structures, probably due to early genetic and/or environmental factors (Krain & Castellanos, 2006). Neuroimaging studies provide a method of direct assessment of brain structure and function; therefore, they allow for testing hypotheses concerning the network of brain dysfunction (Faraone & Biederman, 1998). In general, however, these studies are mainly correlational and typically applied to small samples, which limits the interpretation of the cause-effect relationships, representativeness, and statistical power (Faraone & Biederman, 1998).
Structural neuroimaging studies have localized abnormalities in brain regions and neural networks that are associated with cognitive and behavioral processes consistent with ADHD symptoms (Makris et al., 2009). For example, computerized tomography (CT) and magnetic resonance imaging (MRI) show that ADHD is associated with a global reduction in brain volume and with abnormalities in the frontal and parietal cortex, basal ganglia, and cerebellum (Remschmidt, 2005), as well as the dorsal anterior cingulate cortex and the corpus callosum (Curatolo et al., 2010). Additionally, gray and white matter distribution may be altered in the frontal lobes in ADHD (Krain & Castellanos, 2006), and growing research points to the involvement of the frontostriatal network as a contributor to the pathophysiology of ADHD (e.g., Konrad & Eickhoff, 2010). A recent MRI study in a sample of adults with ADHD also showed significant cortical thinning in a distinct cortical network supporting attention and executive functioning (Makris et al., 2007). One large-scale, longitudinal MRI study revealed cerebellar volume loss in ADHD participants persisted regardless of clinical outcome, though ADHD participants with worse outcomes exhibited a downward trajectory in volumes of both right and left inferior-posterior cerebellar lobes as compared to ADHD participants with better outcomes and controls (Mackie et al., 2007). A metanalytic review of structural brain-imaging studies of ADHD in childhood revealed the most replicated brain alterations were significantly smaller volumes in the dorsolateral prefrontal cortex, caudate, pallidum, corpus callosum, and cerebellum (Seidman, Valera, & Makris, 2005), areas that subserve attention, motivation, and executive functioning. Additionally, a few studies have specifically examined relationships between regional brain volume and behavioral measures such as rating scales and neuropsychological tests. In general, findings from these studies
reveal smaller brain volumes are associated with severity of ADHD behavioral symptoms (Krain & Castellanos, 2006).

Currently, functional imaging techniques are useful for evaluation of medication effects and pathophysiology of ADHD (Bush et al., 2005), and functional imaging studies demonstrate altered patterns of neuronal function in individuals with ADHD versus individuals without ADHD (Remschmidt et al., 2005). There are a wide range of brain networks that may be involved in ADHD symptomatology, including areas related to working memory processes (for details see the following section: WM, ADHD Symptoms, and Brain Function). Utilizing fMRI, multiple studies have found hypofunctional activation of the dorsal anterior cingulate cortex during performance on neuropsychological measures of executive functioning (e.g., Stroop, stop-signal, Go-No Go, and motor timing tasks; Bush et al., 1999; Durston et al., 2003; Rubia et al., 1999; Tamm et al., 2004). Multiple fMRI studies have also shown hypofunctional activation of the lateral frontal cortex (e.g., Rubia et al., 1999; Durston et al., 2003; Bush et al., 1999) during performance of attentional and executive function tasks (Bush et al., 2005). Overall, functional imagining has provided insight into the neural substrates of ADHD, with convergent data indicating front-striatal abnormalities likely play a role in the production of ADHD symptomatology.

Research suggesting relationships between abnormalities in brain structure, ADHD symptoms, and neuropsychological functioning has led to cognitive models of ADHD. Moreover, brain imaging studies help to overcome the limitations of neuropsychological inference (Faraone & Biederman, 1998). These techniques, however, continue to be limited by cost, small sample sizes, and the inverse problem (i.e., using results or observations to calculate cause or source). Cognitive models of ADHD will be discussed in the following sec-
tions, as well as the relationship between structural abnormalities identified in ADHD and WM processes.

**Cognitive Models of ADHD**

As ADHD has been increasingly conceptualized as a neurodevelopmental disorder, models have been developed to explain the associated cognitive and behavioral symptoms. Specifically, these models seek to identify key domains of cognitive functioning in order to identify the underlying neurocognitive processes contributing to ADHD symptom expression. One of the most studied categories of endophenotypes identified for ADHD is executive function (EF; Tripp & Wickens, 2009). EF can be thought of as higher-order cognitive processes that facilitate decision-making by maintaining and integrating information for decision-making (Willcutt, Doyle, Nigg, Faraone, & Pennington, 2005). In particular working memory (WM) and behavioral inhibition (BI) are two areas of EF that have been suggested as possible endophenotypes for ADHD. Though WM and BI are both highlighted in contemporary models of ADHD (Barkley, 2006; Rapport et al. 2008), models vary regarding the primacy and mechanisms of each. Whereas some models suggest WM is a core deficit of ADHD (Rapport et al., 2009), others suggest WM difficulties occur as a result of deficits in BI processes (Barkley, 1997; Sonuga-Barke, 2002). These models are reviewed below.

**Behavioral inhibition models.** Three interrelated processes are involved in BI: inhibition of the prepotent response to a stimulus, stopping of an ongoing response and creating a delay in the decision to respond, and protecting the period of delay in order to allow self-directed responses to occur without interference from other events and responses (Barkley, 1997). There are two main models that highlight the role of BI in ADHD, Barkley's (1997) BI model, and Sonuga-Barke's (2002) dual pathway inhibition model. According to Barkley's
(1997) BI model of ADHD, difficulty with BI sets the stage for deficits in other executive functions, including WM, internalization of speech, and reconstitution, by disrupting control of goal-directed motor behavior (Barkley, 1997). Deficits in BI will be most obvious in situations when a delay of a consequence is imposed on a task, when there is conflict between immediate and delayed consequences of a response, or when a novel response to a problem is necessary (Barkley, 1997).

Similar to the BI model (Barkley, 1997), Sonuga-Barke (2002) hypothesizes that ADHD results from deficits in BI. This model highlights the relationship between ADHD symptoms and difficulty with delay aversion. Delay aversion refers to a learned motivational style in which one chooses smaller, more immediate rewards over larger, delayed rewards (Sonuga-Barke, 2002). In ADHD, delay aversion might work in a few ways. First, when delay averse children cannot escape or avoid delay, they may allocate attention to aspects of the environment that 'speed up' their perception of the passage of time, allowing them to escape subjective experience of delay and accounting for symptoms of inattention. Alternatively, these children may act on the environment to create non-temporal stimulation, resulting in hyperactive behaviors. In addition, impulsive behaviors occur when the child acts on the environment to decrease the delay (Sonuga-Barke, 2002). In this model, ADHD symptoms occur through delay aversion and BI pathways, as well as their interaction, and WM deficits occur subsequent to these difficulties (Sonuga-Barke, 2002).

Many studies provide support for deficits in BI in children with ADHD through use of parent and teacher ratings of hyperactive and impulsive behavior, as well as paradigms such as the go-no-go task, stop-signal task, change paradigm, continuous performance tasks, and delayed response tasks (for a review see Barkley, 1997). However, recent research chal-
lenges the assumption that deficits in WM occur subsequent to BI difficulties. For example, Alderson, Rapport, Hudec, Sarver, and Kofler, (2010) investigated the influence of WM and BI deficits on ADHD symptoms. Their results revealed that WM deficits might underlie BI impairment in children with ADHD, suggesting WM is a core deficit in ADHD, in contrast to BI (Alderson et al., 2010). Similarly, Raiker, Rapport, Kofler, and Sarver (2012) found that WM components accounted for moderate to large portions of increased ADHD-related impulsivity, whereas measures of BI failed to explain, or only partially accounted for, results of various measures of impulsivity (Raiker et al., 2012). Alderson, Rapport, Kasper, Sarver, and Kofler (2012) also experimentally manipulated BI demands and found no discernible effect on objectively measured motor activity in children with ADHD (Alderson et al., 2012). Recent meta-analytic reviews also challenge the BI model of ADHD, and indicate ADHD-related impaired performance on BI tasks is more parsimoniously explained by basic attentional, performance variability, and/or WM process deficits (e.g., Alderson, Rapport, & Kofler, 2007; Lijffijt, Kenemans, Verbaten, & van Engeland, 2005). Therefore, it is possible that WM models may better explain core deficits in ADHD.

**Rapport’s Functional Working Memory Model.** WM refers to a limited-capacity system that has evolved for short-term maintenance and manipulation of information supporting thought processes (Baddeley, 1998). It provides an interface between perception, action, and long-term memory (Baddeley, 2003). WM is most commonly conceptualized as a three-component system comprised of the central executive control system (CE) and two subsidiary systems. The phonological (PH) loop is comprised of a short-term phonological store and an articulatory rehearsal component or loop and is also known as verbal WM (VWM; Baddeley, 2003). The visuospatial (VS) sketchpad, also known as visuospatial WM
(VSWM), is comprised of short-term visual and spatial storage and manipulation components (Baddeley, 2003). The CE is the component of WM that provides overall attentional control of the WM system and is responsible for focusing, dividing, and switching attention. Each of the subsidiary systems allows for the temporary storage of information. The PH is responsible for textual or auditory information and the VS holds visual and spatial information (Baddeley, 2003). Both the PH and VS are ‘time-limited,’ as information fades rapidly from both (Henry, 2012) and capacity-limited, typically to about three or four chunks (Baddeley, 2003). A fourth component of WM, the episodic buffer, is responsible for coordinating information from the PH, VS, and long-term memory. The episodic buffer is thought to be controlled by the CE and provides a mechanism for binding information from different sources within the WM system into coherent episodes (Baddeley, 2000). Like the PH and VS, the episodic buffer is also believed to be limited in capacity (Baddeley, 2000). Figure 1 illustrates Baddeley’s revised WM model.

![Diagram of WM model]

**Figure 1.** The Revised Model of WM (Baddeley, 2000).

Research has shown that the functional organization of WM corresponds to the major components of the WM model in typically developing children from age 4 to 6 years old (Al-
loway, Gathercole, Willis, & Adams, 2004; Gathercole, Pickering, Ambridge, & Wearing, 2004; Swanson, 2008), and the capacity of each increases linearly from age 4 to early adolescence (Gathercole et al., 2004). This research is consistent with theories of developmental variance, meaning there is improvement of cognitive skills steadily over childhood. It has also been suggested that the division of WM into specialized subsystems may not be characteristic of younger children, and young children have a more undifferentiated, nonspecialized memory system (Henry, 2012). Therefore, as the child ages, WM may develop, and the subsystems may become more advanced. In particular, research has shown that children experience a developmental shift around age 6 or 7. Prior to this switch, children rely predominantly on a VS system, and afterward they predominantly rely on the PH system. However, until approximately 10 years of age, the association between CE and PH storage/rehearsal processes remains limited (Gathercole et al., 2004).

Rapport and colleagues’ (2001) functional WM model of ADHD, based on cognitive models of recognition and recall, suggests WM plays a significant role in organizing behavior. In particular, behavioral response is dependent on WM capacity to create, maintain, and match representations of input stimuli and access and maintain representations of behavioral responses suitable to input stimuli (Rapport et al., 2001). The functional WM model suggests WM is a core component of ADHD that occurs upstream of phenotypic features like hyperactivity, impulsivity, and inattention (Rapport et al., 2001). Figure 2 illustrates Rapport and colleagues’ functional WM model of ADHD. Evidence for the WM model of ADHD and specific influence of each subsystem is reviewed next.
Figure 2. The Functional WM Model of ADHD. WM deficits are hypothesized to impact impaired functioning directly (path c) and/or indirectly through behavioral symptoms of the disorder (path a*b). Revised from Kofler et al., (2011).

The importance of the CE functioning as related to WM deficits in ADHD is well established, though the influence of PH and VS subsystems is more controversial. Specifically, research suggests that the CE is highly related to behavioral symptoms of ADHD, and the VS and PH subsystems play a more limited role (e.g. Kofler, Rapport, Bolden, Sarver, & Raiker 2010; Kofler et al., 2011; Raiker et al., 2012; Rapport et al., 2009). For example, utilizing a latent variable approach to measure the contribution of the CE, VS, and PH subsystems, Rapport et al. (2008) identified deficits in all three components of WM, with the largest deficits typically found in the CE, followed by VS and PH subsystems respectively. However, Bolden, Rapport, Raiker, Sarver, and Kofler, (2012) recently found large magnitude between-group effect sizes in children’s phonological storage when more complex verbal stimuli, rather than over-learned stimuli such as number and letters, were used. Importantly, this could also account for comorbidity between ADHD and Specific Learning Disorder in read-
Functional relationships between ADHD-related deficits in the CE component of WM and two primary symptom clusters of ADHD, inattentive (Kofler et al., 2010) and hyperactive (Rapport et al., 2009), have been found. In a study examining the relationship between ADHD-related impulsivity and WM, Raiker and colleagues (2012) found that CE functioning attenuated between-group impulsivity differences. They suggest the significantly larger contribution of the CE in comparison to other tested executive functions highlights deficits in the ability to focus attention and maintain relevant stimuli, monitor ongoing performance, and update memory representations. Additionally, the same study also found the PH storage/rehearsal subsystem also accounted for moderate proportions of increased ADHD-related impulsivity, although VS storage/rehearsal failed to explain between-groups differences in impulsivity (Raiker et al., 2012). As mentioned previously, this could be related to comorbidity between ADHD and Specific Learning Disorder in reading. Similarly, a metanalytic review by Kasper, Alderson, and Hudec (2012) found significant differences in VS and PH between ADHD and control groups, though the CE load of the WM task was also a moderating variable. Karatekin (2004) found no evidence of a deficit in VS or PH subsystems between ADHD and neurotypical children, though impairment in CE functioning in children with ADHD was found. Discrepancies in results may be due to methodological differences, however, such as method of evaluating WM and diagnostic differences in participants with ADHD (e.g., subtypes included or excluded from the sample).

**WM, ADHD symptoms, and brain function.** When considering WM and ADHD, it is notable that correct dopaminergic transmission is essential to WM performance (Goldman-Rakic, 1996) and has been implicated in the pathophysiology of ADHD (e.g., Nigg & Nikolas, 2008). For example, animal research has shown striatal D2 receptors affect dopamine...
tissue and turnover, and D1 receptor activation in the prefrontal cortex, a region related to both WM performance (Kellendonk et al., 2006) and ADHD symptoms (e.g., Seidman et al., 2005). Goldman-Rakic (1996) has also specifically suggested the relationship between D2 receptors and prefrontal circuits may be important to understanding the relationship between dopamine and mechanisms of cognitive processes in psychological disorders. Moreover, dysregulation in catecholamine systems may also lead to a disruption in brain development through increased theta band activity, decreased blood flow to the frontal lobes, striatal lesions, and dopamine deficiency. These neurological irregularities result in cortical underarousal, theoretically leading to deficits in WM processes (Castellanos & Tannock, 2002).

Brain regions associated with WM functioning are also implicated in the pathophysiology of ADHD. Specifically, neural activation of WM in adults involves the bilateral fronto-parietal network (Owen, McMillan, Laird, & Bullmore, 2005), and in neurotypical children these patterns are generally the same, though additional/alternative activation of the premotor and parietal cortex and insula, striatum, and cerebellum have been found (e.g., Thomason et al., 2009). Moreover, in unmedicated children with ADHD, below-baseline WM-related activation patterns in widespread cortico-subcortical networks, including bilateral occipital and inferior parietal areas, caudate nucleus, cerebellum, and functionally connected brainstem nuclei, have been identified (Massat et al., 2012). This suggests a core functional neuroanatomical network underlying WM processes may contribute to the pathophysiology of ADHD (Massat et al., 2012). However, other studies failed to find differences in prefrontal activation patterns between children with ADHD and neurotypical controls during WM tasks (Schecklmann et al., 2010), and further research is needed to clarify this relationship. For example, although Valera, Faraone, Biederman, Poldrack, and Seidman (2005) found that VWM per-
formance did not differ between ADHD adults and control subjects, adults with ADHD showed decreased activity in cerebellar and occipital regions, as well as a trend toward decreased activation in a region of the prefrontal cortex. Moreover, though WM may partially explain ADHD symptoms, it is unlikely that WM theory fully accounts for the expression and maintenance of the disorder. Therefore, additional independent research investigating the contribution of WM to ADHD symptoms and subtypes, as well as the contribution and relationship of other EF processes is paramount. To that end, the proposed study focuses on the relationship between ADHD symptoms and WM capacity.
Chapter 3: Measurement of ADHD and WM

Currently, there is no definitive laboratory or medical test to identify ADHD, and information pertaining to diagnosis and treatment must be obtained from alternative sources. Best practice in ADHD diagnosis requires that a clinician use a multimethod approach and obtain information about symptom presence, pervasiveness, chronicity, and impairment from multiple sources and settings (Handler & DuPaul, 2005). The American Academy of Pediatrics (AAP, 2000) delineated six criteria for ADHD diagnosis, listed in Appendix B. Clinicians often obtain information from subjectively-reported data including interviews and rating scales from teachers, parents and self-report of the child/adolescent. What is interesting, however, is that the neuropsychological tests are not required to make a diagnosis of ADHD (e.g., Gordon and Barkley 1998), although cognitive deficits are considered as phenotypic features of ADHD.

Subjective Data

Clinical interview. Interviews are useful methods for obtaining information about ADHD symptoms in children, and many recognize structured interviews as the “gold standard” in psychology and psychiatry (Pelham, Fabiano, & Massetti, 2005). However, despite expert recommendation for the use of structured and semi-structured interviews as part of ADHD assessment (e.g., Lahey & Wilcutt, 2002), a recent review of assessment methods for children with ADHD suggested DSM-IV-based structured interviews did not add incremental validity to parent and teacher rating scales. Therefore, they should not be used to increase diagnostic precision when differentiating between ADHD diagnosis versus no diagnosis (Pelham et al., 2005). However, given the number of child clinical disorders that include symptoms similar to ADHD (e.g., attention problems, impulsivity), best practice requires
comprehensive evaluation utilizing a clinical interview in order to differentiate between child clinical disorders. For example, multiple meta-analyses suggest findings can be distorted when diagnostic methods of less than gold standard are used (e.g., Alderson et al., 2007; Kofler, Rapport, & Alderson, 2008; Lipszyc & Schachar, 2010). Currently, there are no structured or semi-structured interviews developed to assess ADHD alone, though both structured (e.g., DICA, DISC-IV) and semi-structured (e.g., K-SADS, CAPA) interviews have been developed to assess general psychopathology in children, including specific criteria for ADHD symptoms. Moreover, structured and semi-structured interviews assessing general psychopathology do not currently provide a mechanism for assessing WM. Additionally, existing structured interviews have not been evaluated or modified according to DSM-5 diagnostic criteria. Table 1 provides information for commonly used clinical interviews in ADHD assessment and their strengths/weaknesses.

Table 1.
Assessment Measures Relevant to ADHD Diagnosis

<table>
<thead>
<tr>
<th>Instrument (original author)</th>
<th>Description and Identified Strengths and Weaknesses</th>
<th>Psychometric Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADHD Rating Scales</td>
<td>Sensitivity and specificity generally &gt;94% when differentiating ADHD diagnosis versus normal, age-matched community controls.</td>
<td></td>
</tr>
<tr>
<td>Scale Name</td>
<td>Description</td>
<td>Strengths</td>
</tr>
<tr>
<td>------------</td>
<td>-------------</td>
<td>-----------</td>
</tr>
<tr>
<td>Conners 3 ADHD Rating Scale (Conners 3; Conners, 2008)</td>
<td>This scale provides thorough and focused assessment of ADHD and common comorbid disorders, as well as age and gender-based normative data for ages 6 to 18. Long and short versions, as well as Parent (110 full, 45 short), Teacher (115 full, 41 short), and Self-Report (99 full, 41 short) forms are available. Paper and pencil as well as online versions are available. Strengths: Measures functioning in multiple settings using multiple raters; comprehensive system including multiple subscales; age and gender comparisons available; includes DSM-IV-TR symptom scales that assess for ADHD-HI, ADHD-C, ADHD-I, CD and ODD; good discrimination between clinical and nonclinical children. Weaknesses: Less success discriminating children with ADHD from other clinical diagnoses; subtype classification poor for all subtypes except ADHD-C.</td>
<td>Test-retest reliability = .73-.95(T), .75-.94(P) from 2 to 4 weeks. Internal consistency = .47-.73(P), .44-.97 (T). Interrater reliability = .55(P), .49(P,T).</td>
</tr>
<tr>
<td>ADHD Rating Scale IV (DuPaul et al., 1997)</td>
<td>Developed to provide a two-factor DSM-IV based ADHD checklist for parents and teachers in the context of screening or multimethod assessment in children 5-18 years-old, this 18-item measure consists of questions rated on a 4-point Likert Scale which yields Inattentive, Hyperactive/Impulsive, and Total Scale scores. Strengths: Two-factor model allows for DSM-IV clinical subtypes of ADHD; modified preschool version available to provide assessment of children ages 3-6; time and cost efficient; standardized on large national sample; home version of scale also provided in Spanish. Limitations: Limited use with ethnic minority groups, particularly African-Americans; limited use as a measure of subtype.</td>
<td>Test-retest reliability = .55-.90(T), .70-.86(P) across 4 weeks. Internal consistency = .88-.95(T), .86-.92(P) Interrater reliability = .41-.45 (P,T). Concurrent validity with Conners Rating Scale-Revised subscales = .55-.87(P), .54-.94(T).</td>
</tr>
<tr>
<td>Scale Name</td>
<td>Description</td>
<td>Measurement Characteristics</td>
</tr>
<tr>
<td>---------------------------------------------------------------------------</td>
<td>-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
<td>------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Vanderbilt ADHD Diagnosing Rating Scale (VADRS; Wolraich, Hannah, Pinnock, &amp; Baumgaertel, 1998; Wolraich et al., 2003)</td>
<td>The VADRS includes the 18 ADHD criteria described in the DSM-IV, 8 ODD criteria, 12 CD criteria, and 7 items screening for anxiety and depression. Items are rated by frequency on a 4-point Likert scale. Diagnosis is considered present if scores of 2 (often) or 3 (very often) are checked for the appropriate number of DSM-IV ADHD criteria. A performance section consisting of 8 items rated on a 5-point Likert scale is included to assess academic performance and relationship quality.</td>
<td>Limitations: No effort to enforce DSM ≥2-setting requirement, so prevalence rates based on VADRS may be higher than true rates; age and gender comparisons not available.</td>
</tr>
<tr>
<td>Swanson, Nolan, and Pelham-IV Questionnaire (SNAP-IV; Swanson, 1992)</td>
<td>The long form of the SNAP-IV includes 90 items that assess ADHD, ODD, and overlapping symptoms of all other psychiatric disorders of childhood listed in DSM-IV on a 4-point Likert scale. The short version (SNAP-IV, MTA) includes 26 items that assess ADHD core symptoms of hyperactivity/impulsivity and inattention, and symptoms of ODD. Average rating indices for ADHD-I, ADHD-II, and ADHD-C, and ODD subscales are constructed, and scores about 95th percentile considered clinically relevant.</td>
<td>Limitations: Easy to administer and score; cost-efficient; provides screen for common comorbid conditions and performance rating; available in English and Spanish.</td>
</tr>
<tr>
<td>Brown Attention Deficit Disorder Scales (Brown ADD Scales: Brown, 1996;2001)</td>
<td>The Brown ADD Scales include four forms (Preschool, School-age, Adolescent, Adult) used to evaluate ADD consistently across the lifespan. The Brown ADD scales include six clusters of symptoms frequently associated with ADD. Depending on age of assessment, this measure consists of 40 to 50 items. Parent, teacher, and self-report versions are available. Clinically validated cut score provided.</td>
<td>Sensitivity to change allows for use as a treatment outcome measure.</td>
</tr>
</tbody>
</table>

**Internal consistency = .90-.94(T), .94-.95(P).**

**Interrater reliability = .32 (P,T).**

**Concurrent validity of VADTRS with VADPRS = .29.**

**SNAP-IV: Test-Retest Reliability = .77-.8(T),**

**SNAP-IV, MTA: Internal consistency = .79-.97.**

**Interrater reliability = .43-.47.**
<table>
<thead>
<tr>
<th>Global Rating Scales</th>
<th>Odds ratio generally &lt; 2.0&lt;sup&gt;bb&lt;/sup&gt;</th>
</tr>
</thead>
</table>
| Child Behavior Checklist (CBCL; Achenbach, 1991). | **Internal consistency** = .84(P), .94(T).  
**Test-retest reliability** = .90 (P, 1-week), .71-.77 (P, 1-year), .75 (P, 2-years), .96 (T, 15-days), .73 (T, 2-month & 4-month).  
**Interrater reliability** = .93-.96 (interviewer), .79 (P), .61-.62 (T).  
**Concurrent validity** = .59 (CBCL attention subscale, Conners), .80 (T, Conners);  
DSM-Oriented Scales **Internal consistency** = .71-.89<sup>p</sup>  
**Sensitivity** = 38.1% and **Specificity** = 100% at cut-point of T ≤ 70 for DSM-IV diagnosis of ADHD.  |

A multiaxial empirically based assessment of children ages 4 to 18, this 118-question inventory consists of eight scales measuring behavior characteristics, and three scales measuring impairment in social, school, and other activity settings. Items are rated on a three-point Likert scale. Total internalizing, externalizing, and competency can be calculated, and subscales converted to T-scores normalized by age and gender with clinically relevant thresholds established for both syndrome (T = ≥ 67) and competency (T = ≤ 33) subscales.<sup>1</sup> DSM-Oriented Scales, constructed through agreement in experts’ ratings of the preexisting items’ consistency with DSM-IV diagnostic criteria, are also available.<sup>6</sup> Parent, teacher, youth self-report, and observation forms are available. **Strengths:** A theoretical approach to construction yields more objective, reliable, and homogenous groupings than clinically derived scales<sup>16</sup>; aids in discriminating comorbid from non-comorbid cases of ADHD<sup>5</sup>; cost effective, minimizes physician’s time.<sup>7</sup> **Weaknesses:** May not adequately assess clinical problems in diverse populations.<sup>8</sup>
Behavior Assessment Scale for Children (BASC; Reynolds & Kamphaus, 1992). This multidimensional measure assesses adaptive and problem behaviors, and includes preschool, child, and adolescent versions, as well as structured developmental history (SDH), and student observation system (SOS). It consists of 130 items rated on a 4-point frequency scale. **Strengths:** Time and cost efficient; comprehensive; ratings produce various scales and composites that may be contrasted and compared to identify relative strengths and weaknesses; items analyzed for bias during development, and items clearly biased toward gender and race/ethnicity dropped; General Norms, Clinical Norms, Clinically-Identified ADHD group, and LD-Identified Norms available. **Weaknesses:** Neither the SDH nor the SOS have norms, and little specific guidance for how they are to be interpreted.

### Attention Problem Composite
- **Internal consistency:** .85-.87(T), .76-.81(P).<sup>5</sup> **Test-retest reliability:** .83-.92(T), .78-.92(P).<sup>5</sup> **Interrater reliability:** = .63-.69(T), .56-.73(P) **Concurrent Validity** with corresponding CBCL and CRS established.
- **Sensitivity** = 76.2% and **Specificity** = 87% at cut-point of T ≤ 70 for DSM diagnosis of ADHD.<sup>5</sup>

### Structured Interviews

#### Diagnostic Interview for Children and Adolescents (DICA; Reich, Weller, and Herjanic, 1997)
The DICA is a structured interview based on the DSM criteria. It efficiently screens for a broad range of behavioral problems, including symptoms of ADHD. Stein-Reich Critical Items identify high-risk features by highlighting responses that reflect a potential for dangerous behavior. Parent and child/adolescent versions are available for ages 6 to 17. The parent version includes information about the prenatal health and early development of the child/adolescent. **Strengths:** Comprehensive; computerized-assisted version of the DICA (can be self-administered) available. **Weaknesses:** Administration and evaluation of data time consuming (approximately 5-20 minutes for each of the 28 possible categories), graduate level training necessary for administration.<sup>v</sup>

- **Internal consistency:** > .9.
- **Test-retest reliability:** = .78-.86 (P), .24-.43 (SR).<sup>u</sup> **Interrater reliability:** = -.01-.34 (P,SR)<sup>u</sup>
### Diagnostic Interview Schedule for Children Version IV (DISC-IV; Shaffer et al., 2000)

The DISC is a structured psychiatric diagnostic interview for parents or children/adolescents aged 6 to 18. It was developed for research but is useful in clinical settings. The DISC-IV is based on DSM-IV criteria and assesses for more than 30 psychiatric diagnoses. Questions reference the two weeks, four weeks, and year prior to the interview.  

**Strengths:** Can be administered by trained lay interviewers; most questions answered "yes," "no," "somewhat," or "sometimes"; low in cost; self-administration possible; available in several languages; direct relation to DSM-IV categories; includes validity subscales; *Weaknesses:* Sociocultural appropriateness questionable; lengthy administration.

### Internal consistency  
- $\text{DISC-IV} = .6(P), .1(Y), .48 (P+Y)$.  
- Test-retest reliability  
  - ADHD = .79(P), .42(Y), .62 (P+Y).  
  - Interrater reliability  
    - .70(P), .1(Y), .48(P+Y) for symptom counts, .65(P), .19(Y), .56(P+Y) for criteria + impairment.

### Semistructured Interviews

#### Kiddie Schedule for Affective Disorders and Schizophrenia (K-SADS; Kaufman et al., 1997)

The K-SADS is a DSM-III-R/DSM-IV based semi-structured diagnostic interview for assessing current and past episodes of psychopathology in children/adolescents ages 6-18. It is primarily for use in research settings and covers a broad spectrum of child psychiatric diagnoses. The K-SADS is administered by interviewing the parent and child, as well as achieving summary ratings that include all sources of information (parent, child, school, chart, and other).  

**Strengths:** Wide age range; multiple reporters, same scale used for screening/assessment; direct relation to DSM-IV categories. *Weaknesses:* Lengthy (90-120 minutes); administration and interpretation require clinical training/experience.

**Interrater agreement** high (range: 93% to 100%). Test-retest reliability $\kappa$ coefficients for present diagnoses ADHD = .67.  

**Convergent validity** with CBCL attention problems scale excellent. **Discriminant validity** between children with ADHD and Bipolar disorder demonstrated.
| Child and Adolescent Psychiatric Assessment (CAPA: Angold et al., 1995) | The CAPA is a DSM-III based diagnostic interview combining structured and semi-structured formats, for use with children and parents. The child version is designed for children ages 9-18. The parent version may be appropriate for parents of younger children as well. Administration is by a trained interviewer. **Strengths:** Available in English and Spanish; relates directly to DSM-IV diagnostic categories; computer or electronic scoring available. **Weaknesses:** Lengthy (1.5 hours); parent and youth report only; formal training required for administration. | Significant relations with CBCL scores.  
  
Notes: T= Teacher, P = Parent;  
\( ^a \) (Conners, 2008),  
\( ^b \) (Hale, How, Dewitt, & Coury, 2001),  
\( ^c \) (Sullivan & Riccio, 2007),  
\( ^d \) (DuPaul et al., 1998),  
\( ^e \) (DuPaul et al., 1997),  
\( ^f \) (McGoey et al., 2007),  
\( ^g \) (Pappas, 2006),  
\( ^h \) (Wolraich et al., 1998),  
\( ^i \) (Wolraich et al., 2003),  
\( ^j \) (Lucas, 2007),  
\( ^k \) (Bussing et al., 2008),  
\( ^l \) (Achenbach, 1991),  
\( ^m \) (Ostrander, Herman, Sikorski, Mascendaro, & Lambert, 1998),  
\( ^n \) (Biederman et al., 2005),  
\( ^o \) (Achenbach et al., 2003),  
\( ^p \) (AAP, 2000),  
\( ^q \) (Russell-Nethers, 1996),  
\( ^r \) (Mano, Davies, Klein-Tasman, & Adesso, 2009),  
\( ^s \) (Reynolds & Kamphaus, 1992),  
\( ^t \) (Pelham et al., 2005),  
\( ^u \) (Boyle et al., 1993),  
\( ^v \) (Reich et al., 1997),  
\( ^w \) (Shaffer et al., 2000),  
\( ^x \) (Sharp et al., 2010),  
\( ^y \) (Kaufman, Birmaher, Brent, Rao, & Ryan, 1997),  
\( ^z \) (Angold et al., 1995),  
\( ^{ab} \) (Collett, Ohan, & Myers, 2003);  
\( ^{bc} \) (Weiss, Hechtman, & Weiss, 2001),  
\( ^{cc} \) (Rucklidge & Tannock, 2002). |  |

**Rating scales.** Alternative to interview methods, the AAP (2000) highlights the “clinical option” of using questionnaires and rating scales developed to quantify ADHD symptoms, and strongly recommends their use. Parent, teacher, and self-report child/adolescent rating scales may be used to assess the type and degree of ADHD symptoms and associated impairment, identify the situational pervasiveness of behavioral problems, or identify the presence of other comorbid disorders. When considering behavioral rating scales and assessment of ADHD, it is important to note that there are generally two types of questionnaires and rating scales: specific scales developed to review and quantify behavioral characteristics of ADHD (e.g., Conners-3, SNAP-IV, DSM-IV ADHD Rating Scale), and global, nonspecific measures developed to assess a variety of behavioral conditions (e.g., BASC, CBCL). According to the AAP (2000), though the former are strongly recommended for use when evaluating children for ADHD (guideline 3A and 4A), the latter are not recommended.
in diagnosis of ADHD (guideline 3B and 4B), though they may be useful for other purposes. However, it is also important to note that during initial evaluation, global scales, which contain multiple factors/clinical dimensions are preferred to narrow-band instruments, in order to understand whether or not a child meets diagnostic criteria for ADHD or his/her symptoms are better accounted for by another disorder or medical condition. Specific ADHD rating scales have been shown to accurately differentiate children who do and do not meet criteria for the ADHD diagnosis, though global rating scales are generally not as useful for making this distinction (AAP, 2000; see Table 1 for detailed psychometric properties). One notable exception is the CBCL, which includes an 'attention' factor scale and provides separate T-scores and percentiles for attention and hyperactivity/impulsivity based on a large standardization sample, as well as a DSM ADHD factor score that is highly correlated with whether or not the child had an ADHD diagnosis (Achenbach, 1991). It is also important to note that most ADHD-specific rating scales do not include impairment ratings, age of symptom onset, or symptom chronicity. Additionally, though some ADHD-specific rating scales screen for common comorbid disorders such as ODD and CD (e.g., Conners, VARS, SNAP-IV), global measures can provide a more comprehensive assessment of comorbidity. Therefore, revising ADHD-specific rating scales to include questions relevant to these limitations, or adding a global measure (e.g., CBCL) may be advisable (Pelham et al., 2005).

**Neuropsychological Assessment**

According to the AAP (2000), use of diagnostic tests for diagnosis of ADHD is not routine (Guideline 6), and additional tests contribute little to establishing a diagnosis of ADHD. Gordon and Barkley (1998) point out psychological testing is not required to make a diagnosis of ADHD, and no current tests have adequate classification accuracy to do so,
though some testing may be useful for establishing general cognitive ability and academic achievement levels. Neuropsychological assessment may also be useful for detailed treatment advice and outcome measures (Dineen & Fitzgerald, 2010) and discernment of whether attentional problems are a result of other cognitive deficits (Sugalski, Scott, & Cleary, 2008).

**WM assessment.** The functional WM model suggests WM is a core component of ADHD occurring upstream of phenotypic features (Rapport et al., 2001); therefore, evaluation of WM in ADHD may lead to advances in diagnosis, treatment, and outcomes, as well as a better understanding of ADHD subtypes. It is notable that previous research indicates WM deficits in ADHD seem to be more closely related to the CE, which is involved in processing/manipulating verbal and visuospatial information, relative to VS and PH subsystems (Rapport et al., 2008), which are primarily short-term storage/rehearsal systems. Additionally, although one metanalytic review found greater between-groups effect sizes in VS rather than PH processes (Martinussen, Hayden, Hogg-Johnson, & Tannock, 2005), other metanalytic reviews found larger between-groups effect sizes for PH relative to VS processes (Kasper et al., 2012, Willcutt et al., 2005). However, it is important to note that differences between reviews may be reflective of differences between tasks and analyses. Specifically, Martinussen et al. (2005) grouped tasks as storage versus CE as a function of the amount of mental manipulation necessary for task completion. In contrast, Kasper et al. (2012) separated tasks by PH or VS modality, and then examined CE as a moderator variable. Therefore, differences in analysis may have impacted the degree to which CE functioning was accounted for.

Research by de Freitas Messina and colleagues (2006) has found WM may be a useful construct for differentiating between subtypes of ADHD. Specifically, investigation of
WM abilities in children with three subtypes of ADHD revealed significant differences in WM reaction time between subtypes. The ADHD-I group showed more WM difficulties than other subtypes, and children with ADHD in general had more difficulty with auditory rather than visual memory items (de Freitas Messina, Tiedemann, de Andrade, & Primi 2006). However, other studies have failed to find general WM deficits in children with ADHD (Jonsdottir, Bouma, Sergeant, & Scherder, 2005), and some have suggested WM deficits in ADHD are better accounted for by associated disorders, such as specific language impairment (Hutchinson, Bavin, Efron, & Sciberras, 2012). Additionally, it is notable that none of the above studies has demonstrated sufficient positive and negative predictive power for ADHD diagnosis at the individual level. In order for WM to become a useful construct for ADHD assessment, measurement of WM must improve. Specifically, tasks that consistently elicit the WM construct, enable differentiation of WM subcomponents, and are similar between experimental research and clinical assessment are necessary.

Though useful for assessment of ADHD symptoms and evaluation of comorbid conditions from the perspective of multiple reporters, clinical interviews, and behavioral rating scales used in typical ADHD assessment do not provide assessment of WM performance in children, and additional measures are necessary to evaluate WM performance. These generally fall into the following categories: span tasks, computerized assessment measures, cognitive subtests, and rating scales. The following subsections provide an overview of methodology for each category, examples of commonly used measures within each category, and strengths and weaknesses of each. Currently, there is no “gold standard” measure for assessment of working memory, and no single approach is guaranteed to engage the neural circuitry of working memory (Jarrold & Touse, 2006).
**Span tasks.** In clinical neuropsychology, span tasks are often considered one of the most common methods for assessing WM capacity (Beblo Macek, Brinkers, Hartje, & Klaver, 2004). However, according to Baddeley’s working memory model (2003), span tasks primarily rely on rehearsal and buffering processes. Simple span tasks require the individual to store information for short-term use. For example, participants may be asked to repeat increasingly longer lists of letters or numbers (e.g., Wechsler, 2003), or tap a lengthening sequence (e.g., Milner, 1971) presented by the examiner. However, as manipulation of the information is not introduced and there is minimal engagement of the CE, simple span tasks are a measure of short-term memory, the ability to hold information for a limited time (Jarrold & Towse, 2006), rather than WM capacity (Vock & Holling, 2008). Despite these limitations, span tasks are often used (e.g. Beblo et al., 2004), and span tasks allow for differentiation of verbal and visuospatial processes by changing task structure or demand, consistent with a domain-specific view of WM (i.e., separate processes are engaged by VWM and VSWM; Coccini, Logie, Della Sala, MacPherson, & Baddeley, 2002). For example, digit or letter span tasks (e.g., Wechsler, 2003) utilize verbal, numerical information to assess VWM, whereas tasks such as the Corsi block tapping task (Milner, 1971) are loaded with spatial content and designed to assess VSWM. Additionally, spatial span tasks have been shown to be a sensitive measure of cognitive deficits in ADHD (EF = 1.34, P < .01; Alloway & Passolunghi, 2011).

In contrast to simple span tasks, complex span tasks require both storage and processing of information, engage the CE, and as such, are theoretically a more accurate measure of WM processes (Beblo et al., 2004). Generally, the storage component of complex span tasks refers to retention of briefly presented information, and the processing component is
manipulation or transformation of the information (Oberauer, 2005). A variety of complex span tasks for assessing VWM have been described in the literature, and though the stimuli and processing components vary across tasks, common to all of these tasks is the presentation of to-be-remembered stimuli in combination with a demanding secondary processing task (Conway et al., 2005). For example, variations of reading span tasks (Daneman & Carpenter, 1980), operation span tasks (Turner & Engle, 1989), and counting span tasks (Case, Kurkland, & Goldberg, 1982) are all commonly utilized complex span tasks. Though a variety of complex span tasks measuring VWM have been described, fewer tasks utilizing visuospatial information are available (Vock & Holling, 2008).

Methodologically, complex span tasks have proven to be a reliable and valid measure of WM capacity. For example, a variety of complex span tasks have shown construct validity, including both convergent validity with one another and other tasks of complex cognition, discriminant validity with tasks that reflect automatic processing, and predictive validity in successfully predicting complex cognition (See Table 5; Conway et al, 2005). However, misuse of span tasks, including inconsistent administration, hinders their reliability clinically (Conway et al., 2005). Moreover, most span tasks are experimental, and their psychometric properties have not been established in large representative samples, as is necessary for use within clinical practice settings. Additionally, it is important to note that the CE component of WM involves distinct yet interrelated processes such as focusing, dividing, and switching attention (Baddeley, 2007), and recent metanalyses suggest differential brain activation occurs according to what WM process is being engaged by task demands (e.g., Nee et al., 2013; Wager & Smith, 2003). This suggests multiple WM tasks assessing individual processes should be a part of comprehensive WM assessment. In ADHD research, mathematical and
linguistic complex-span tasks may show group differences between ADHD and control, as well as between ADHD subtypes (Diamond, 2005). See Table 2 for additional examples and psychometric properties of complex span tasks.

Table 2.

*Working Memory Assessment Measures and their Association with ADHD*

<table>
<thead>
<tr>
<th>Task/Instrument (Original Author)</th>
<th>Description and Identified Strengths and Weaknesses</th>
<th>Psychometric Properties</th>
<th>Association with ADHD (when available)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Span Tasks</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Counting Span (Case et al., 1982)</td>
<td>Common to all of these tasks is presentation of to-be-remembered stimuli in combination with a demanding secondary processing task. <em>Strengths</em>: Strong predictors of other cognitive abilities; commonly used and well validated; Convergent, discriminate, and predictive validity noted. <em>Weaknesses</em>: Subtle changes in administration can cause measurement error; possibility for maintenance rehearsal and the forming higher-order chunks.</td>
<td>Test-retest reliability = .15&lt;sup&gt;a&lt;/sup&gt;; Internal consistency = .668-.768&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Mathematical and linguistic complex-span tasks might show group differences between ADHD and control, as well as ADHD subtypes.</td>
</tr>
<tr>
<td>Operation Span (Turner &amp; Engle, 1989)</td>
<td></td>
<td>WM Factor Loading = .7&lt;sup&gt;i&lt;/sup&gt;; Internal consistency = .698-.814&lt;sup&gt;a&lt;/sup&gt;; Test-retest reliability = .7-.8&lt;sup&gt;a&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Backward Digit Span (BDS; Wechsler, 1981)</td>
<td></td>
<td><em>Split-half reliability</em> = .85&lt;sup&gt;e&lt;/sup&gt;; <em>Concurrent validity</em> with SJS = .57-.70&lt;sup&gt;a&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Reading/Listening Span (RS/LS; Daneman &amp; Carpenter, 1980)</td>
<td></td>
<td>Test-retest reliability = .62&lt;sup&gt;e&lt;/sup&gt;; WM Factor Loading = .81&lt;sup&gt;f&lt;/sup&gt;; <em>Concurrent validity</em> with BDS = .45&lt;sup&gt;e&lt;/sup&gt;; Internal consistency = .697-.788&lt;sup&gt;a&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Size Judgment Span (SJS; Cherry, Elliot, &amp; Reese, 2007)</td>
<td></td>
<td><em>Concurrent validity</em> with LS = .57-.70&lt;sup&gt;b&lt;/sup&gt;; <em>Concurrent validity</em> with BDS = .55&lt;sup&gt;g&lt;/sup&gt;</td>
<td></td>
</tr>
</tbody>
</table>

**Computerized Assessment Measures**
<table>
<thead>
<tr>
<th>Change Detection Tasks (VSWM-Luck &amp; Vogel, 1997; VWM-Thomason et al., 2009)</th>
<th>Computerized programs that overload the processing system by presenting a large array of stimuli in a time-limited fashion. <em>Strengths:</em> Standard administration, multiple methods of scoring and process evaluation; <em>Weaknesses:</em> Paradigms not explicitly validated in children, nor directly compared with other WM measures.</th>
<th>Participants able to retain approximately four items in WM, similar to previous estimates of WM capacity. All set size effects statistically significant for VSWM task ( P &lt; .0001 ).</th>
<th>Thomason et al. (2009) utilized these tasks with a sample of neurotypical children and adults, though no studies have yet evaluated the use of these paradigms in participants with ADHD.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automated Working Memory Assessment (AWMA; Alloway, 2007)</td>
<td>Computerized measure for educational professionals to screen for WM problems in ages 4-22. Provides three measures each of VSWM, VWM, verbal short-term memory, and visuospatial short-term memory. <em>Strengths:</em> Developed based on Baddeley (2000) revision of WM model; standardized for non-professionals; quick and effective screen with age related cut-off scores; multiple measures of each construct; <em>Weaknesses:</em> Poor test-retest reliability and internal consistency.</td>
<td>Test-retest reliability for WM subtests = .79-.90 in individuals aged 4.5-22.5; Mean scores on WMI (WISC-IV) higher for average versus low WM groups as classified by the AWMA; <em>Internal consistency</em> = .35-.66.</td>
<td>AWMA has been used to investigate short-term and WM profiles in children within ADHD, as well as between children with ADHD and other developmental disorders. Children with ADHD have a unique WM profile compared to other group, and WM impairment across verbal and visuospatial domains.</td>
</tr>
</tbody>
</table>

**Cognitive Subtests**
<table>
<thead>
<tr>
<th>Working Memory Index (Wechsler, 1981)</th>
<th>Intelligence test battery frequently used to measure general cognitive abilities in children. WMI includes Digit Span, Letter Number Sequencing, and Arithmetic subtests. <strong>Strengths:</strong> Commonly used in clinical psychology, account for significant variance in cognitive WM construct; <strong>Weaknesses:</strong> Lack of complexity on forward digit span; Arithmetic influenced by mathematical ability and does not add unique variance; Tasks are all verbal rather than visual/spatial.</th>
<th>WMI (WAIS-III) $R^2 = .38$, Digit Span $R^2 = .33$, Letter-Number Seq. $R^2 = .28$, Arithmetic $R^2 = .14$; Mean scores on WMI (WISC-IV) higher for average versus low WM groups as classified by the AWMA; WMI (WISC-IV) sufficient to assign correct group membership between low and average WM children (WMI <em>Sensitivity</em> = 80%, Digit Span <em>Sensitivity</em> = 91%, Letter-Number Sequencing <em>Sensitivity</em> = 63%).</th>
<th>Separately, scores in Arithmetic and Backward Digit Span are significantly lower in children with ADHD; Forward Digit Span does not reveal this discrepancy.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stanford Binet Intelligence Scales, Fifth Edition (SBV; Roid, 2003)</td>
<td>Intelligence test battery frequently used to measure general cognitive abilities in children. Includes variations of complex span tasks to measure both VWM (Last Word) and VSWM (Block Span). <strong>Strengths:</strong> WM measures relatively independent with academic knowledge or skill; <strong>Weaknesses:</strong> Only one task each measures VSWM and VWM</td>
<td>WM Factor <em>Split-half Reliability</em> = .92; VSWM <em>Split-half Reliability</em> = .88; VWM <em>Split-half Reliability</em> = .84; Concurrent and Divergent validity of WM subtests with other cognitive measures demonstrated.</td>
<td>WM factor scores for children with ADHD significantly lower than WM scores for control group; children with ADHD did not differ significantly from control group on other factor scores.</td>
</tr>
</tbody>
</table>

*Rating Scales*
| Brief Rating Inventory of Executive Function (BRIEF; Gioia, Isquith, Guy, & Kenworthy 2000) | Teacher and parent behavior report inventory designed to assess EF in 5-18 year-old children via 8 empirically derived scales, including WM. *Strengths:* Measures everyday executive functioning ability in real world settings; useful for general ADHD classification; *Weaknesses:* Lengthy form; items are highly redundant with the DSM-IV ADHD criteria resulting in high reliability but limited unique variance; less accurate for subtype classification.  

*Test-retest reliability = .79-.88 over 2 weeks; Internal consistency = .80-.98; Interrater reliability = .82 (parents)-.88 (teachers); Convergent validity between BASC Attention and Hyperactivity and Inattention subscales and BRIEF subscales demonstrated.*  

| Working Memory Rating Scale (WMRS; Alloway, Gathercole, Kirkwood, & Elliot, 2008) | Consists of 20 descriptions of problem behaviors associated with WM deficits to be rated by teachers. *Strengths:* Quick to administer; simple scoring; no training necessary for administration; *Weaknesses:* Shy, bored, or unmotivated children may be incorrectly identified with WM problems.  

*Convergent validity with AWMA and WMI (WISC-IV) demonstrated; Internal Consistency = .978; Substantial relationship between direct and rating-based assessment of WM reported.*  

<table>
<thead>
<tr>
<th>Notes:</th>
</tr>
</thead>
</table>
**Computerized assessment measures.** Computerized tasks provide a mechanism for reducing some problems inherent in complex span tasks. Computerized complex span tasks enable standardized presentation of the stimuli at regular intervals and the potential for random selection of trials and list lengths (Woods et al., 2011). In addition, computerized complex span tasks allow for adaptive presentation of stimuli, reducing ceiling affects possible in traditional complex span tasks (Woods et al., 2011). Other types of computerized WM tasks have also been developed. One method to reduce potential for higher-order chunking of familiar patterns or associations between items is to overload the processing system when stimuli are presented, so more information is in time-limited stores than possible to rehearse or encode before the time-limit ends (Cowan, 2000). This procedure forces participants to use secondary memory and allocate additional attentional resources to recover information no longer contained in STM by exceeding 'primary memory' (Unsworth & Engle, 2007) or the 'focus of attention' (Cowan, 1988). Utilizing this technique, Luck and Vogel (1997) developed a match-to-sample, or change detection VSWM task. Match-to-sample or change detection tasks are tasks in which a sample stimulus is presented, and then a test stimulus is presented that is either the same or different from the sample stimulus. The participant must choose whether the test stimulus matches the sample stimulus. Specifically, Luck and Vogel (1997) presented an array of colored shapes in the sample and test stimulus, increasing the number of stimuli presented in the array to augment WM load. A similar VWM task has also been developed, in which letters are presented in the sample and test array (Thomason et al., 2009). Although though these tasks have shown validity in adult samples (Bo, Jennet, & Seidler, 2011; Luck & Vogel, 1997;), they have not been extensively validated in children. Thomason et al. (2009) utilized these tasks with a sample of neurotypical children and adults,
though no studies have yet evaluated the use of these paradigms in participants with ADHD. Moreover, it is important to note that most of the currently available computerized assessment measures are recognition rather than free recall tasks. Recognition tasks provide a copy of the information to be found in memory, and representation of perceptual input is compared with that stored in memory (Rapport et al., 2000). Conversely, recall tasks require the individual to access representations stored in memory (Rapport et al., 2000). Recognition and recall tasks have been shown to require different cognitive processes (Kahana, Rizzuto, & Schneider, 2005) and are also related to different anatomical brain sites (Cabeza et al., 1997). Therefore, recall tasks may place more demand on WM than recognition tasks, which could account for discrepancies in results of WM performance in ADHD (Rapport et al., 2008).

Alloway (2007) developed the Automated Working Memory Assessment (AWMA) for screening individuals from four to 22 years old for WM problems. This measure consists of tasks that measure short-term memory, as well as VWM and VSWM. The verbal tasks consist of variations of simple span tasks for measuring short-term memory and complex span tasks for VWM assessment. The visuospatial short-term memory assessment includes variations of simple span tasks, whereas the VSWM measure includes both a complex span task and match-to-sample task. In contrast to other computerized WM assessment measures, the AWMA has been validated in children (Alloway et al., 2008) and has been specifically utilized to assess WM in children with ADHD. For example, AWMA has been used to investigate WM profiles in children with ADHD, in comparison to neurotypical children and those with Developmental Coordination Disorder (DCD), Specific Language Impairment (SLI), and Asperger Syndrome (Alloway et al., 2009a). Results show children with ADHD have a unique WM profile compared to other groups, and they show WM impairment across verbal
and visuospatial domains (Alloway et al., 2009a). For additional information about computerized WM assessment measures, see Table 2.

**Cognitive subtests.** In addition to WM specific measures, WM scales are included in instruments commonly used in clinical psychology, such as the Wechsler Intelligence Scale for Children, Fourth Edition (WISC-IV; Wechsler, 2003). Understanding whether clinical measurement of WM is comparable to measurement of WM in experimental research requires examination of the task structures that make up WM subscales.

The WISC-IV includes a Working Memory Index (WMI) made up of Digit Span and Letter-Number Sequencing subtests. Digit Span includes both simple (forward digit span) and complex (backward digit span) tasks, and scoring combines the total number of digit strings correctly repeated in both conditions (Wechsler, 2003). Unfortunately, the Digit Span subtest may be measuring more than WM ability, as forward digit span does not include a processing component (Hill et al., 2010). This is important to ADHD research, as studies have shown children with ADHD perform worse than controls on backward (complex), but not forward (simple), digit and spatial span tasks (Mariani & Barkley, 1997; McInnes et al., 2003). Similarly, a metanalysis revealed higher mean differences between ADHD and comparison groups in verbal short-term (digits forward; 0.47) versus verbal CE WM functioning (digits backward; 0.56). However, when one study with outlying data was removed, results of the metanalysis revealed mean differences were similar between measures of verbal short-term (0.47) and CE WM (.43) between groups (Martinussen et al., 2005). The Letter-Number Sequencing subtest provides children with a random sequence of letters and numbers, and children repeat the sequence back in predetermined order. This task has high face validity as a WM construct, requiring the processing component neglected in Digit Span, and the aca-
demic skill prerequisite is not as pronounced as in Arithmetic (Hill et al., 2010). The WISC-IV also includes an Arithmetic subtest that may be used if the Digit Span or Letter-Number Sequencing subtest is spoiled. This subtest consists of verbally presented arithmetic word problems. Although this task seems to manipulate working memory load, it relies heavily on mathematical abilities, making it less than ideal for WM assessment (Hill et al., 2010). Additionally, it is important to note that all WMI subtests are verbal tasks, and therefore do not provide a measure of spatial WM functioning.

Conceptually, it seems the tasks in the WMI are different from those used in cognitive psychology to measure WM and, excepting the Letter-Number Sequencing subtest, they may not be measuring the same construct identified in cognitive literature (Shelton et al., 2009). However, Hill et al. (2010) compared similar tasks from the Wechsler Adult Intelligence Scale, Third Edition (WAIS-III; Wechsler, 1997) WMI to other commonly used WM tasks, finding the clinical measures seemed to be measuring a construct similar to that studied in cognitive psychology. Still, despite similarity in constructs, results revealed the Arithmetic subtest was a nonsignificant predictor of the WM construct and did not account for unique variance. Moreover, results modestly supported inclusion of Matrix Reasoning and Vocabulary subtests for improvement of the WMI in WM assessment (Hill et al., 2010). It is also notable that this study was completed in adults, and a similar study evaluating the similarity of the WISC-IV WMI and cognitive WM measures among children is not available. Additionally, metanalysis reveals that although FSIQ is significantly lower in ADHD than control subjects, subtests of the WMI showed similar effect sizes to other subtests included in FSIQ (Frazier, Demaree, & Youngstrom, 2005), suggesting WMI subtests do not reliably differentiate ADHD from non-ADHD participants. Overall, this suggests further research is warrant-
ed on WM measurement in clinical psychology, including its similarity to WM constructs in cognitive and experimental research, as well as potential adaptation of current paradigms. See Table 2 for additional information about clinical WM subtests.

**Rating scales.** Most behavior rating scales do not assess executive functioning (EF), though the Conners 3 (2008) and BASC-2 (2008) are notable exceptions. Moreover, none of the available ADHD rating scales are designed to include assessment of WM capacity. Specific scales that measure EF in general, as well as WM in particular, however, are available. For example the Brief Rating Inventory of Executive Function (BRIEF; Gioia et al., 2000) was developed to assess EF from an everyday perspective, and provide a measure of everyday executive functioning ability in real world settings, in contrast to isolated assessments produced by clinic-based tests of EF (Gioia et al., 2000). The BRIEF is a parent and teacher-rating scale comprised of eight empirically derived subscales: inhibition, shifting, emotional control, initiation, planning/organization, organization of material, monitoring, and WM. Two global scales, behavioral regulation and metacognition, as well as validity scales (negativity and inconsistency) are also available (Gioia et al., 2000). In addition to assessing WM, studies have shown the BRIEF is useful for ADHD assessment. For example, studies comparing ADHD-I, ADHD-C, and control groups have consistently found ADHD groups had higher ratings (indicating worse WM) from parents and teachers on the WM scale, though this did not differentiate between ADHD groups (Gioia et al., 2000; McCandless & O’Laughlin, 2007). Additionally, other BRIEF index scores, Metacognitive and Behavioral Regulation, have been found to differ significantly between ADHD subtypes (McCandless & O’Laughlin, 2007). For more information regarding BRIEF psychometric properties, see Table 2.
Although the BRIEF shows promise in WM and ADHD assessment, one drawback is its lengthy format, since it measures multiple domains of EF. In contrast, Alloway and colleagues (2009b) developed the Working Memory Rating Scale (WMRS). This 20-item scale enables teachers to identify children at risk for learning difficulties due to WM deficits and utilizes quick administration and simple scoring. Items are descriptions of behaviors typical of children with WM deficits (e.g., “The child raised his hand but when called upon, had forgotten his response”), rated on a Likert scale.

Finally, when considering the use of rating scales such as the BRIEF and WMRS for measuring executive functioning, it is notable that recent research shows EF rating scales correlate weakly or nonsignificantly with laboratory tasks that measure EF (Barkley, 2011). Furthermore, Barkley (2011) suggests rating scales provide a more ecologically valid measurement of the ability of the individual to use EF in daily activities. Therefore, using rating scales in combination with neuropsychological tests of executive functioning may provide a more comprehensive view of adaptive functioning of the individual. For information on psychometric properties of the WMRS, see Table 2.

It is important to note that there are a variety of modalities and measures currently available for WM assessment, with associated strengths and weaknesses. The majority of these have been developed for experimental use in cognitive psychology, though associations between WM constructs measured in cognitive and clinical psychology have some support (Hill et al., 2010). While many standardized measures exist to assess both ADHD and WM, there is no single “gold standard” measurement for either. Instead, a multitrait-multimethod assessment of ADHD should be the “gold standard,” as this allows for examination of similar and dissimilar traits through a variety of methods (Campbell & Fiske, 1959). This type of
approach would also allow for subjective (e.g., parent and teacher report) as well as objective measurement of symptoms (e.g., WM assessment). The measures reviewed above generally have adequate psychometric properties when used appropriately; however, using them in combination would add reliability and validity to WM assessment. Additionally, although the WM model of ADHD suggests deficits in WM functioning may be a core deficit of ADHD, at present there are no laboratory or clinical WM tasks that differentiate ADHD from non-ADHD children at the individual level (Rapport et al., 2000). Moreover, Rapport et al. (2000) notes that current tests and tasks used to differentiate ADHD from other disorders have been borrowed from existing neuropsychological or specialized batteries. Therefore, though they provide interesting correlational data (e.g., categorical diagnosis of ADHD is related to higher error scores), they fail to provide essential information regarding why particular errors are made or what the underlying processes and mechanisms by which these processes operate are (Rapport et al., 2000). Additionally, imaging methods are not yet used for clinical diagnostic decision-making (except to rule out medical and/or neurological causes for ADHD-like presentation), due to group-averaged designs that do not allow for reliably distinguishing normal from abnormal at the individual level (Bush et al., 2005). Therefore, this remains an important area for future research.
Chapter 4: Rationale for the Present Study

Although converging evidence suggests WM is a core deficit in ADHD (Rapport et al., 2001), and research suggests the functional neuroanatomical network underlying WM processes in ADHD may contribute to the pathophysiology of ADHD (Massat et al., 2012), some studies fail to find a relationship between WM and ADHD (e.g., Karatekin, 2004; Siegel & Ryan, 1989) or differences in WM brain activation patterns between children with ADHD and neurotypical controls (e.g., Schecklemann et al., 2010). For the purpose of the current study, two explanations for discrepant results will be focused upon, both of which are related to the importance of defining the construct being measured and methods of measuring the construct.

WM Construct and Measurement

Conflicting findings regarding the relationship between ADHD and WM could be explained by differences in the measurement of WM, including the degree to which paradigms are consistently engaging WM processes. As mentioned previously, there are multiple methods for measuring WM, and a variety of tasks available within methods. As such, there is no “gold standard” for WM assessment; however, one must be careful to choose a technique that appropriately measures the construct. Specifically, increased research on WM capacity indicates average WM capacity is not “seven, plus or minus two” (Miller, 1956). Instead, capacity limit ranges from three to five, though chunking strategies can augment perception of capacity limits (Cowan, 2000). Therefore, tasks that measure true WM capacity are those that limit chunking by overloading the processing system with stimuli that cannot be rehearsed or encoded before the time limit is up, block rehearsal through presentation of alternative stimu-
li, evaluate WM capacity as a function of performance discontinuities caused by capacity limit, or limit indirect effects of capacity limit (i.e., grouping; Cowan, 2000).

In particular, WM assessment using digit span tasks has been highly criticized, as research utilizing these tasks indicates WM capacity can be much greater than three to five (e.g., Ericson & Kirk, 2001) due to chunking of material. Other studies, however, show span task capacity limits are closer to four, in the form of numbers chunked together (Wilding, 2001). Therefore, although reliability of WM measurement using span tasks has been shown (see Table 2), this research is limited by the validity of the construct being assessed. Consequently, tasks should be chosen based on current understanding of WM. Automatic presentation and scoring of span tasks could provide increased methods of scoring and process evaluation (Redick et al., 2012; Woods et al., 2011), thereby reducing inherent problems with complex span tasks. For example, computerized scoring could evaluate WM based on response rate, thereby enabling detection of chunking, rather than scoring based on number correct. Alternatively, changing the task altogether may be especially useful. For example, computerized change-detection tasks assess WM according to number of items held and operated on in WM (Luck & Vogel, 1997), a methodology based on current conceptualization of WM. This task, however, lacks validation in children. Therefore, the first aim of this study is to examine the use of change-detection paradigms in neurotypical children and validate their use.

Moreover, as previously discussed, it is important to understand the similarities and differences in constructs being measured by experimental research and the clinical tools being utilized in practice. Specifically, conceptually the tasks in clinical measurement of WM such as the WMI of Wechsler intelligence tests appear to be different from those used in
cognitive psychology to measure WM. Therefore, with the exception of the Letter-Number Sequencing subtest, they may not be measuring the same construct identified in cognitive literature (Shelton et al., 2009). Although Hill et al. (2010) compared similar tasks from the WAIS-III WMI to commonly used experimental WM tasks and found the clinical measures seemed to be measuring a construct similar to that studied cognitive psychology, results also modestly supported inclusion of additional subtests for improvement of the WMI in WM assessment (Hill et al., 2010). Additionally, a similar study evaluating the similarity of the WISC-IV WMI and cognitive WM measures among children is not available, suggesting further research on WM measurement in clinical psychology, including its similarity to WM constructs in cognitive and experimental research, is necessary. Therefore, the second aim of this study is to explore the relationship among measures of WM used in experimental research and those used in clinical settings.

**ADHD Classification**

**Continuous versus categorical classification.** Diverging findings in ADHD and WM impairment could be explained by differences in sample characteristics of the studies. As previously discussed, ADHD is conceptualized differently depending on the diagnostic classification system being utilized. Within DSM-IV classification, ADHD was diagnosed categorically, with no specifiers for severity (APA, 2000). Currently, however, the DSM-5 includes specifiers for severity within categorical classification of ADHD. A mild presentation requires few if any symptoms in excess of those required for diagnosis and minor impairment in functioning. A severe impairment requires many symptoms in excess of those necessary for diagnosis, or several particularly severe symptoms that result in major impairment. A moderate presentation is symptoms or impairment between “mild” and “severe”
classification (APA, 2013). Therefore, despite specifiers for severity now being included in diagnosis, individuals still either meet criteria for ADHD or they do not. Moreover, as ADHD severity was only recently included in DSM classification, previous studies have not evaluated impairment level within samples.

Although classification systems define ADHD categorically (e.g., DSM, ICD-10), there has been ongoing debate regarding whether ADHD should be best conceptualized categorically or on a continuum. Those who advocate for categorical classification of ADHD suggest similarities between ADHD subtypes and HKD indicate ADHD is best defined categorically (Lee et al., 2008). Specifically, one study found symptom severity does not predict impairment, and degree of impairment does not increase across more severe diagnostic categories in all or most criteria, as would occur if ADHD were a single dimension of psychopathology. Instead, the groups tend to be more similar than dissimilar across clinical correlates, suggesting categorical conceptualization is appropriate (Lee et al., 2008). Therefore, although studies that utilize DSM criteria for classifying ADHD are likely to include children with a less severe presentation, whereas those using ICD-10 criteria will include only more extreme presentations of ADHD symptoms, both should be reflective of the same underlying dimension of psychopathology.

In support of a continuous view of ADHD, research using latent class analysis suggests latent clusters of ADHD symptoms may provide clinical value in identifying individuals who fall below DSM-IV-TR diagnostic criteria thresholds yet still have significant impairment (Elia et al., 2009). Additionally, although biological factors associated with ADHD suggest categorical classification may be appropriate, these findings do not preclude ADHD from being considered an extreme end of a spectrum or set of traits that occurs throughout
the population (Graham, Seth, & Coghill, 2007). Moreover, if ADHD is best classified continuously, studies utilizing DSM diagnostic criteria may fail to identify a relationship between ADHD and WM, although a similar study using more stringent ICD-10 criteria might find significance due to more serious symptoms and associated impairment. Therefore, measurement of ADHD symptoms as a continuous dimension could provide a method for better understanding the neurological underpinnings of ADHD and understanding the relationship between WM and ADHD.

**ADHD subtypes.** Although the stability of general ADHD symptoms over time has been demonstrated (e.g., Lahey, Pelham, Loney, Lee, & Willcutt, 2005), the constancy of subtypes is less supported. For example, in a longitudinal study, Lahey and colleagues (2005) found that shifts from one subtype to another were common in individuals who continued to meet criteria for ADHD over an eight-year period. Specifically, the ADHD-HI subtype often changes to the ADHD-C as the child ages (Lahey et al., 2005), and symptoms of hyperactivity tend to decrease with age, whereas symptoms of inattention increase. These results suggest ADHD-C and ADHD-I may be valid subtypes, whereas ADHD-HI may be best thought of as an early manifestation of ADHD in children who will ultimately meet criteria for ADHD-C (Willcut Chhabildas, & Pennington, 2001).

Alternatively, some researchers have suggested ADHD-I should be classified as a separate disorder, distinct from ADHD-C, based on literature suggesting individuals with ADHD-I tend to be more shy, withdrawn from peers, female, and vulnerable to internalizing disorders, while individuals with ADHD-C are more likely to be male, experience peer rejection, have earlier symptom onset, and comorbid externalizing disorders (Milich, Balentine, & Lynam, 2001). However, a metanalysis conducted by Codding, Eckert, Lewandowski, and
Fiese (2005) suggested that although ADHD-C and ADHD-I are different, they are not necessarily distinct, since both showed similar patterns of effect sizes for various subtype comparisons across domains of functioning.

Overall, more research is needed in order to understand the structural validity of subtypes within ADHD. As specific subtypes of ADHD are often included (or excluded) from samples, understanding whether subtypes are reflective of the same underlying pathology or separate disorders is paramount. It is possible that discrepancies in findings regarding the relationship between WM and ADHD could be explained by differences in sample subtypes utilized. For example, whereas many studies do not report ADHD subtypes included in the sample (Klingberg Forssberg, & Westerberg, 2002), others include only one subtype in the sample (e.g. ADHD-C; Holmes et al., 2010), potentially restricting the generalizability of results to other subtypes (e.g. ADHD-I and ADHD-HI). Moreover, latent class analysis has shown potential in a limited number of ADHD studies (e.g., Elia et al., 2009; Ostrander et al., 2008), further indicating measurement of symptoms, rather than heterogeneous subtypes, may lead to greater understanding of the neurological underpinnings of ADHD and the relationship between ADHD and WM, as well as increase understanding regarding appropriate subtype classification. In addition, previous research has differential memory profiles across different developmental disorders (Alloway et al., 2009a). Specifically, children with attention problems were impaired across both verbal and spatial domains (Alloway et al., 2009a). Therefore, although WM function is expected to predict ADHD symptoms, it is also possible that ADHD symptom domains could be associated with specific WM profiles. Moreover, given that discrepancies in WM impairment may be explained by ADHD categorization, the third aim of the present study seeks to question the relationship between WM impairment and
symptoms of ADHD (continuous model), as compared to ADHD diagnosis and WM impairment (categorical model).

**Additional variables.** In order to better examine the WM model of ADHD, it is important to consider other potential variables that might contribute to the relationship between WM and ADHD symptoms. Specifically, phonological awareness and anxiety will be assessed. These variables were chosen due to high comorbidity between ADHD and Learning Disorders as well as ADHD and anxiety disorders (Pliszka, 2000). Moreover, both learning disorders and anxiety have been associated with WM deficits. Specifically, multiple studies have associated learning difficulties and WM performance (e.g., Gathercole et al., 2006; Alloway, Gathercole, Kirkwood, & Elliot, 2009c). In regard to anxiety, Eysenck et al. (2007) suggest that anxiety disrupts the ability to focus attention appropriately, which can lead to reduced capacity to inhibit incorrect responses, increased distractibility, impaired performance in dual-task situations, and impaired task-switching. Previous studies have shown that anxiety disrupted VSWM but not VWM performance (Shackman et al., 2006). Moreover, anxiety is likely to be more disruptive when the stimuli are perceived to be threat-related, or when task stimuli are nonsalient or inconspicuous (Eysenck et al., 2007). For example, individuals with math anxiety have been shown to demonstrate smaller WM capacity, especially when assessed with a computation-based span task (Ashcraft & Kirk, 2001). Although these variables are not a main focus of the current study, and no specific aims or hypotheses are associated with them, their influence on relationships between WM and ADHD will be explored.
Model for the Present Study

To further investigate and clarify the relationship between WM and ADHD, the present study will utilize a quasi-experimental design examining ADHD symptoms and WM functioning in children. The current investigation will seek to validate measurement of WM in children, providing support of paradigms to be used with children both clinically and in experimental research. Specifically, the construct validity of the WMI will be assessed, as well as its relationship to results of computerized change-detection paradigms used in experimental research. Ensuring that paradigms utilized are engaging WM processes, rather than simply activating short-term memory, as well as examining the relationship between paradigms used both clinically and experimentally with children, would theoretically lead to better understanding of the relationship between WM and ADHD, as well as greater diagnostic efficiency and better intervention strategies. Moreover, although Rapport’s functional WM model suggests deficits in WM processes result in the phenotypic features of ADHD (hyperactivity, impulsivity, and inattention), discrepant results have been found in studies assessing WM functioning in children with ADHD (e.g., Karatekin et al., 2004; Martinussen et al., 2005; Pennington & Ozonoff, 1996; Siegel & Ryan, 1989; Willcutt et al., 2005). However, these studies are limited by individual differences between children in the samples, including ADHD subtype and severity of diagnosis. Therefore, this study seeks to compare WM memory functioning in children classified through a categorical conceptualization of ADHD with a continuous model of ADHD, evaluating the relationship between symptoms of ADHD and WM functioning in children.
Chapter 5: Aims and Hypotheses

Aims of the Current Study

(1) To validate the use of computerized change-detection paradigms in neurotypical children and compare the performance of children to that of adults.

(2) To investigate the relationship between WM functioning as assessed clinically with the WISC-IV and experimental measures of WM such as computerized change-detection paradigms and computerized span tasks.

(3) To examine the phenotypic features of ADHD (hyperactivity, impulsivity, and inattention) in children as measured by the Conners-3 ADHD Rating Scale and their relationship to WM functioning when continuous ADHD symptoms versus categorical ADHD classification is used.

(4) To examine whether computerized change-detection paradigms can better predict the phenotypic features of children with ADHD than the WISC-IV WMI.

Hypotheses

Validation of computerized change-detection paradigms in children. (1) Performance of children on arrays of 1-3 items will be nearly perfect and decline systematically with set size increase from 4 to 12 items, consistent with results of Luck and Vogel (1997) in an adult sample, as well as the performance of the adult comparison sample recruited for the current study, and theories suggesting one way to accurately assess WM is by overloading the processing system (Cowan, 2000). Additionally, mean WM capacity of children and adults are not expected to be significantly different, although (2) Age-related changes on WM measures are expected, and WM capacity is expected to increase with age, consistent with previous research (e.g., Alloway et al., 2004; Gathercole et al., 2004; Swanson, 2008).
(3) Age-related differences between VSWM and VWM capacity are expected. Younger children are expected to have greater differences between VSWM and VWM than older children, consistent with research showing children tend to rely on VSWM until around age 6 or 7, at which time they begin relying more on VWM (Gathercole et al., 2004).

Clinical versus experimental WM measurement. (4) The WISC-IV WMI and Wechsler subtests such as Digit Span and Letter-Number sequencing will account for a significant amount of variance in criterion constructs commonly utilized in WM literature (computerized change-detection paradigms and span tasks), consistent with results of Hill et al. (2010) in an adult sample. (5) The Arithmetic subtest will not add unique variance and will be excluded from the best predictor model of WM, consistent with results of Hill et al. (2010) in an adult sample. (6) Addition of subtests outside of those that currently make up the WMI may be able to account for additional variance in WM by accounting for executive attention functions and controlled retrieval of items from secondary memory. Specifically, Vocabulary and Matrix Reasoning will account for additional unique variance in the WM construct, consistent to results of Hill et al. (2010) in an adult sample.

WM and ADHD symptoms. (7) WM capacity will be related to number of symptoms of ADHD in the domains of hyperactivity, impulsivity, and inattention. Higher WM capacity will be related to fewer symptoms, whereas lower WM capacity will be related to a higher number of symptoms. Given that developmental disorders have specific memory profiles (Alloway et al., 2009a), it is hypothesized that (8) a continuous measurement of ADHD symptoms will lead to greater classification accuracy of high versus low WM than categorical classification of ADHD. In other words, WM differences may not be found across categorical classifications of ADHD. However, WM capacity measures will be related to the con-
tinuous measurement of ADHD symptoms. (9) ADHD symptoms will be related to both verbal and visuospatial WM domains, consistent with previous research finding ADHD is related to deficit in both verbal and visuospatial domains of WM (e.g. Alloway, Rajendran, & Archibald, 2009).

**Classification of ADHD via the WMI and change-detection tasks.** (10) WM as measured by change-detection tasks will result in better classification of ADHD than the WMI. In other words, the WM scores in change-detection tasks will better predict the categorical measurement of ADHD than the WMI scores.
Chapter 6: Method

General Procedure

All measures were administered by the PI or a trained research assistant. Test administration took place in a private, quiet office setting. Informed consent was obtained from parents, as well as assent from children prior to administration of any measures. Participants then completed the two-subtest WASI-II followed by the WM measures, the CTOPP-2 Phonological Awareness subscale, and RCMAS. Administration of verbal and visual computerized WM tasks were counterbalanced. Testing time for children was approximately one hour. While children completed testing, parents completed a brief demographic and screening form and the Conners 3-P which took approximately 25 minutes. See Appendix D for the demographic and screening form. Adult participants only completed the demographic and screening form and the change-detection tasks, and testing time was approximately 45 minutes.

IRB approval was obtained from Eastern Michigan University.

Measures

Computerized change-detection tasks. The change detection visuospatial (VSWM) and verbal working memory (VWM) tasks reported in Bo et al. (2011) were employed. The tasks were originally modified from Luck and Vogel (1997) and Thomason (2009). Both computerized tasks begin with presentation of a fixation cross, followed by presentation of a sample array for 100ms. The fixation cross is then presented again for 900ms, followed by a 2,000ms presentation of the test array. The test array consists of either the same stimulus as the sample array, or an array with one element changed. After viewing each sequence of arrays, participants are asked to press the corresponding key to indicate if the test array was the same (s) or different (d) from the sample array. In each task, all arrays are arranged along an
invisible concentric circle around a fixation cross. For the VSWM task, the arrays consist of two to eight (array size) colored circles (radius = 1; randomly selected from red, orange, yellow, green, blue, violet, pink, white, black, and brown). On each trial, the test array is either the same as the sample array, or changed by one color. Therefore this task relies on the detection of change in color at different locations. See 3 for an example of the VSWM array. For the VWM task, the arrays consist of letters (size = 1 inch; randomly selected from Q, R, G, B, H, A, N, F, I, T, E, and D). The sample arrays are uppercase letters, whereas the test arrays are lowercase, forcing participants to encode the letters. On each trial, the test array is either the same as the sample array, or changed by one letter. Therefore, this task relies on detection of letter change. See Figure 4 for an example of the VWM array. Working memory capacity will be estimated using the formula: $K = \text{Size of array} \times (\text{observed hit rate} – \text{false alarm rate}; \text{Vogel & Machizawa, 2004})$. The average $K$ across all array sizes will then be computed to represent working memory capacity for each participant.

*Figure 3. Example of VSWM Change-Detection Task.*
Figure 4. Example of VWM Change-Detection Task.

**Computerized complex span task.** The Automated Working Memory Assessment (AWMA) is a computerized measure of WM originally developed to screen individuals from age 4 to 22 for WM problems (Alloway et al., 2008). It was developed based on Baddeley’s (2000) revised WM model and provides three measures each of verbal and visuospatial aspects of short-term and working memory. In the current study, one VWM subtest and one VSWM subtest was utilized, and these also comprise the screening form of the AWMA, which takes approximately five to ten minutes to administer. Specifically, in the Listening Recall VWM subtest, the participant hears a series of individual sentences and decides if the sentence is true or false. After each block, the participant recalls the last word of each sentence in correct order. Blocks range from one to six sentences. In the Spatial Recall VSWM subtest, the participant views a picture of two shapes in which the shape on the right has a red dot above it. The participant must identify whether the shape on the right is the same or op-
posite the shape on the left. The shape on the right may also be rotated. Following each trial, the participant must recall the location of each red dot on the shape in correct order. See Figure 5 for samples of AWMA tasks.

![AWMA WM Tasks](image)

**Figure 5.** Example of AWMA WM Screening Tasks.

**WISC-IV.** The WISC-IV is a comprehensive intelligence test for children administered by a trained individual, with normative data for individuals aged 6-16:11. The WISC-IV provides four index scores (Verbal Comprehension Index, Perceptual Reasoning Index, Processing Speed Index, Working Memory Index), as well as full-scale intelligence quotient (FSIQ). However, only the subtests in the Working Memory Index (Digit Span, Letter-Number Sequencing, and Arithmetic) were administered for the purposes of the present study, and completion averaged approximately 15 minutes. The reliability of these subtests is high, ranging from .87-.90 (Williams, Weiss, & Rolfhus, 2003).

**WASI-2.** The WASI-II is a brief standardized measure for intelligence screening. It provides an estimate of (FSIQ) on more comprehensive batteries, yet may be completed in 15 minutes. The current study used the two-subtest version of the WASI-II, which is comprised
of the Vocabulary and Matrix Reasoning subtests. Scores on these subtests are used to generate an estimated FSIQ, which has a .93 reliability in children (Maccow, 2011). Additionally, these subtests may be substituted for their counterparts on the WISC-IV (Zhou & Raiford, 2011). Normative data for individuals ages 6-90 years is available, and a trained individual should complete standardized administration.

**CTOPP-2.** The CTOPP-2 is a measure utilized to assess reading-related and phonological processing skills. The current study used only the Phonological Awareness composite (PACS), which is comprised of three subtests for four to six year olds (Elision, Blending Words, and Sound Matching) and three subtests for seven year olds (Elision, Blending Words, and Phoneme Isolation). The PACS assesses awareness of and access to the phonological structure of oral language (Wagner et al., 2013).

**Conners 3-P.** The Conners 3-P is a parent report measure that provides a thorough assessment of ADHD symptoms in children aged 6-18, as well as comorbid disorders such as Oppositional Defiant Disorder and Conduct Disorder. T-scores for the following scales are provided: General Psychopathology, Inattention, Hyperactivity/Impulsivity, Learning Problems, Executive Functioning, Aggression, Peer Relations, Family Relations, ADHD Inattentive, ADHD Hyperactive-Impulsive, Oppositional Defiant Disorder, and Conduct Disorder. In order to enhance interpretation of the Conners 3-P subscales, it is important to delineate the difference between the Inattention and Hyperactivity/Impulsivity subscales, the ADHD Inattentive, ADHD Hyperactive/Impulsive, and the ADHD Inattentive, Hyperactive-Impulsive, and Combined symptom counts. The Inattention and Hyperactivity/Impulsivity subscales were designed to assess the general content areas of Inattention and Hyperactivity/Impulsivity respectively. Therefore, these scores include items assessing both the general
concept of inattention or hyperactivity/impulsivity and problems associated with inattention or hyperactivity/impulsivity, as well as some DSM-specific items. The ADHD Inattentive and ADHD Hyperactive/Impulsive subscales are made up only of items containing symptom level information from the DSM. In contrast to the other Conners 3-P scales, the ADHD Inattentive, Hyperactive/Impulsive, and Combined symptom counts are not *t*-scores. Rather, these scores represent number DSM ADHD symptoms endorsed by the rater within each ADHD presentation.

Internal consistency coefficients for Conners 3 total sample ranges from .77 to .97, two to four week test-retest reliability coefficients range from .71 to .98, and inter-rater reliability coefficients range from .52 to .94. The Conners 3-P can be completed independently by a parent in approximately 20 minutes. The continuous measurement of ADHD symptoms depended on the number of symptoms reported on this scale, and the categorical diagnosis depended on classification according to DSM based subscales on this scale.

**Revised Children’s Manifest Anxiety Scale, Second Edition (RCMAS-2).** The RCMAS-2 is a self-report measure consisting of 49 items designed to assess severity of anxiety in children aged 6-19. The first 10 items comprise a short-form Total Anxiety scale. The 10 item short-form can be completed in less than five minutes, and was used in the current study to screen for anxiety. The overall internal consistency reliability for the RCMAS and subscales (*α* = .92; *α* = .75-.86 respectively) is good, and test-retest reliability is satisfactory (*r* = .76).

**Adult self-report measures.** Adult self-report measures were administered in order to characterize the adult sample. However, none of the self-report measures administered to the adult participants were utilized in analyses.
Beck Anxiety Inventory (BAI). The BAI is a 21-item self-report inventory designed to assess anxiety severity in individuals ages 17-80 (Beck & Steer, 1993). High internal consistency (α = .92) and one-week test-retest reliability (r = .75) were demonstrated (Beck, Epstein, Brown, & Steer, 1988).

Beck Depression Inventory (BDI). The BDI is a 21-item self-report inventory designed to assess depression severity in individuals ages 13 and over (Beck, Steer, & Carbin, 1988). High internal consistency in both non psychiatric (α = .81) and psychiatric (α = .86) has been demonstrated (Beck et al., 1988). High concurrent validity with the Hamilton Psychiatric Rating Scale for Depression has also been reported (Beck et al., 1988).

Conners Adult ADHD Rating Scale (CAARS). The CAARS is a self-report measure designed to assess, diagnose, and monitor ADHD symptoms in adults (Conners, Erhardt, Epstein, Parker, Sitarenios, & Sparrow, 1999). It is designed for individuals 18 years and older and contains four factor-derived subscales (inattention/memory problems, hyperactivity/restlessness, impulsivity/emotional lability, and problems with self-concept) and DSM-based ADHD symptom scales. The CAARS has demonstrated high internal consistency reliability (α = .86-.92), and test retest reliability (r = .89; Erhardt, Epstein, Conners, Parker, & Sitarenios, 1999).

Data Analysis

Data analyses were conducted using Statistical Package for Social Sciences (SPSS), Version 22. Within standardized measures, missing data were accounted for according to the instrument manual. Preliminary descriptive statistics were examined to identify outliers, normality of distribution, multicollinearity between variables, and internal reliability within scales. Bivariate correlations were used to identify relationships between WM capacity in
children and adults (Hypothesis 1 and 2), VSWM and VSM capacity as assessed by change
detection tasks (Hypothesis 3), between WISC-IV WM subtests, AWMA-2 subtests and
computerized change-detection tasks (Hypothesis 4, 5, and 6), and between ADHD symp-
toms as assessed by the Conners 3-P and WM tasks as assessed by the WISC-IV WM sub-
tests, AWMA-2 subtests, and computerized change-detection tasks (Hypothesis 7 and 9). T-
tests were utilized to assess mean differences between child and adult samples (Hypothesis
1), and a Fisher r-to-Z transformation was calculated to evaluate the relationship between
VSWM, VWM, and age (Hypothesis 2). For relationships revealing significant or near-
significant correlation, regression analyses were used to explore predictor-outcome relation-
ships. Specifically, linear stepwise multiple regression analyses were conducted in order to
quantify the relative predictive value of each predictor for the predictor-outcome relation-
ships of interest (Hypotheses 3, 4, 5, 6, 7, 8, and 10). Finally, receiver operating characteris-
tic (ROC) curves were utilized to evaluate the classification accuracy of WM measures for
ADHD (Hypothesis 10).
Chapter 7: Results

Participants

Participants included 50 male children recruited via fliers and word of mouth in the community. Sample size was determined based on the necessity for at least ten participants per predictor variable (Field, 2009). Children ranged from age 6 to 12, with a mean age of 9.12. The age range recruited ensured eligibility for the standardized clinical neuropsychological measures to be administered, yet avoided high within-group variation due to age-related developmental differences of executive function among children. Moreover, research has shown the underlying structure for WM is in place for children as young as four and five years old (Alloway, Gathercole, & Pickering, 2006), indicating inclusion of children as young as six years old in the current study was appropriate. Additionally, other studies assessing WM in children have previously included similar age ranges (e.g., children aged 5.1-11.5; Alloway et al., 2009b). The children were predominantly white (78%) and right-handed (80%). Child education ranged from kindergarten to sixth grade. Since presence of ADHD symptoms rather than ADHD diagnosis is being measured in the current study, a formal diagnosis of ADHD was not necessary for inclusion; however, 20% of the sample (i.e., 10 participants) were previously diagnosed with ADHD. Children were excluded from the study prior to data collection if parents reported a history of a specific learning disorder, closed head injury with loss of consciousness, other neurological disorder, or ASD. Exclusion criteria also included a score below the Low Average range (<80 FSIQ-2 on the Wechsler Abbreviates Scale of Intelligence, Second Edition, two subtest version; WASI-II; Wechsler, 2011). Only two potential participants were excluded, one because of a suspected ASD and the other because the parents chose not to participate and withdrew consent. In the former case, the
child was nonverbal and unable to comply with tasks. His family was informed that he did not meet criteria for study participation, given the gift card, and thanked for their willingness to participate. In the latter case, the parents withdrew consent after testing began due to discomfort providing family demographic information. They were also provided with the gift card and thanked. Thirty-four percent of children received some form of special education services, primarily Speech Therapy (24%). Children prescribed medication for ADHD (6%) were unmedicated at time of testing. See Table 3, below, for additional demographic information.

Table 3.

*Child Participant Demographic Characteristics*

<table>
<thead>
<tr>
<th></th>
<th>M (SD)</th>
<th>Range</th>
<th>N (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Child Age</td>
<td>9.12 (1.76)</td>
<td>6-12</td>
<td></td>
</tr>
<tr>
<td>Child Race</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>White</td>
<td>39 (78%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Biracial</td>
<td>5 (10%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>African American</td>
<td>3 (6%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hispanic</td>
<td>2 (4%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Asian</td>
<td>1 (2%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Child Grade</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kindergarten</td>
<td>3 (6%)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
First 9 (18%)
Second 7 (14%)
Third 10 (20%)
Fourth 5 (11%)
Fifth 6 (7%)
Sixth 7 (3%)

Child Handedness

Right 40 (80%)
Left 9 (18%)
Ambidextrous 1 (2%)

Child Psychological Diagnosis (by history)

ADHD 10 (20%)
Oppositional Defiant Disorder 1 (2%)

Child Medication Prescription

ADHD 3 (6%)
Other 8 (16%)

Special Education Services
<table>
<thead>
<tr>
<th>Category</th>
<th>Count</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speech Therapy</td>
<td>12</td>
<td>24%</td>
</tr>
<tr>
<td>ADHD</td>
<td>1</td>
<td>2%</td>
</tr>
<tr>
<td>Reading, Writing, or Math</td>
<td>2</td>
<td>4%</td>
</tr>
<tr>
<td>504 Plan</td>
<td>1</td>
<td>2%</td>
</tr>
<tr>
<td>Gifted and Talented</td>
<td>1</td>
<td>2%</td>
</tr>
<tr>
<td>None</td>
<td>33</td>
<td>66%</td>
</tr>
</tbody>
</table>

**Parental Education - Father**

<table>
<thead>
<tr>
<th>Category</th>
<th>Count</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>High School Diploma</td>
<td>18</td>
<td>36%</td>
</tr>
<tr>
<td>Technical or Associates Degree</td>
<td>3</td>
<td>15%</td>
</tr>
<tr>
<td>Bachelor’s Degree</td>
<td>12</td>
<td>24%</td>
</tr>
<tr>
<td>Graduate Degree</td>
<td>5</td>
<td>10%</td>
</tr>
</tbody>
</table>

**Parental Education - Mother**

<table>
<thead>
<tr>
<th>Category</th>
<th>Count</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Did Not Complete High School</td>
<td>3</td>
<td>6%</td>
</tr>
<tr>
<td>High School Diploma</td>
<td>9</td>
<td>18%</td>
</tr>
<tr>
<td>Technical or Associates Degree</td>
<td>12</td>
<td>24%</td>
</tr>
<tr>
<td>Bachelor’s Degree</td>
<td>20</td>
<td>40%</td>
</tr>
<tr>
<td>Graduate Degree</td>
<td>6</td>
<td>12%</td>
</tr>
</tbody>
</table>

In addition to the 50 children, 15 neurotypical male adults were recruited to serve as a
developmental comparison group for performance on change-detection paradigms. This sample size is similar to previously reported results of similar studies (e.g., 10 participants, Luck & Vogel, 1997). Adult participants ranged in age from 19 to 28 years old with a mean age of 21.4. Adults were predominantly white and right-handed (86.7%). One participant had a diagnosis of ADHD. No participant had a history of epilepsy or other neurological disorder. None were prescribed or taking stimulant medication at the time of testing. See Table 4 for additional demographic information.

<table>
<thead>
<tr>
<th>Table 4. Adult Participant Demographic Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Age</strong></td>
</tr>
<tr>
<td>----------</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

Ethnicity

- White: 13 (86.7%)
- Biracial: 1 (6.7%)
- African American: 1 (6.7%)

Education

- College Sophomore: 11 (73.3%)
- Bachelor’s Degree: 4 (26.7%)

Handedness
<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Right</strong></td>
<td></td>
<td>13 (86.7%)</td>
</tr>
<tr>
<td><strong>Left</strong></td>
<td></td>
<td>2 (13.3%)</td>
</tr>
</tbody>
</table>

**Psychological Diagnosis**

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ADHD</strong></td>
<td></td>
<td>1 (6.7%)</td>
</tr>
<tr>
<td><strong>None</strong></td>
<td></td>
<td>14 (93.3%)</td>
</tr>
</tbody>
</table>

**Medication Prescription**

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Non-ADHD Medication</strong></td>
<td></td>
<td>1 (6.7%)</td>
</tr>
<tr>
<td><strong>None</strong></td>
<td></td>
<td>14 (93.3%)</td>
</tr>
</tbody>
</table>

**History of Special Education Services**

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Speech Therapy</strong></td>
<td></td>
<td>1 (6.7%)</td>
</tr>
<tr>
<td><strong>None</strong></td>
<td></td>
<td>14 (93.3%)</td>
</tr>
</tbody>
</table>

---

**Preliminary Data Analyses**

Neuropsychological tests were administered and scored according to standard administration described in their respective manuals. Within standardized assessment measures, raw scores were converted to age- and gender-corrected standardized scores depending on the measure, and missing data was accounted for in accordance with the instrument manual. Within child measures, the RCMAS-2 and Conners 3P were examined for internal reliability based on inter-item correlations. A Cronbach’s alpha value greater than or equal to .70 is considered acceptable (Santos, 1999). The Conners 3P demonstrated acceptable internal reliability (α = .95). In contrast, the RCMAS-2 demonstrated internal-consistency reliability
somewhat below the acceptable range ($\alpha = .57$). Inter-item correlations were examined to identify items for deletion; however, this would not have resulted in a significant increase in the internal consistency reliability of the scale. Although the published reliability of the 49-item RCMAS-2 and each of the subscales is good (full scale $\alpha = .92$; subscale $\alpha = .75-.86$), as $\alpha$ is strongly influenced by the length of the scale (Steiner, 2003), it is possible that the short form demonstrates reduced internal consistency reliability due to being comprised of only 10 items. Adult self-report measures were not utilized in analyses, and were administered only to characterize the sample. Within the adult self-report measures, Cronbach’s alpha for the Conners Adult ADHD Rating Scales (CAARS) subscales was acceptable (subscales $\alpha = .70 - .86$), with the exception of the DSM-IV Inattentive Symptom subscale ($\alpha = .62$). Inter-item correlations were examined to identify items for deletion and revealed that deletion of Item 64, “I am distracted by things going on around me” would result in an acceptable alpha coefficient ($\alpha = .72$). The internal consistency of the Beck Anxiety Inventory (BAI) was acceptable.

**Normality of distribution.** All measures were assessed for normality of distribution by examining skew and kurtosis coefficients, as well as visual analysis of histograms and box plots. Skew and kurtosis coefficients between -1 and +1 are generally considered to be within normal range, though values outside this range may also be valid (Mertler & Vannatta, 2005). Skew and kurtosis coefficients were generally within acceptable range for all child measures, with the exception of the VWM change detection task (1.43 skew). Additionally, Shapiro-Wilks (S-W) tests were conducted for all scales in order to determine if the scores in the sample significantly deviated from a normal distribution. A significant W statistic indicates the distribution is significantly different from the normal distribution (Field, 2009). In
small data sets (n < 100), if the S-W test has a p < .001, the data may not be normal (Wolwerton, 2015). This value was significant at the .001 level for WISC-IV Digit Span LDSF, and Conners 3-P ADHD symptom counts. This suggests that with the exception of these aforementioned scales, the rest of the measures did not significantly violate assumptions of normality. As the measures with S-W tests significant at the .001 level were not variables in regression analyses, no transformations were performed. Moreover, the change-detection task was the only measure with significant kurtosis. Theoretically, this measure should not result in a negative value; however, descriptive statistics reveal children's data is clustered in the 0 to 2 range, with some negative values (i.e., response accuracy less than random guessing). The distribution range for this measure was also very small, which likely contributed to problems with normality. Finally, there is no literature to suggest or support how to interpret any transformed data with this task. Therefore, as this task has never been evaluated in a child population, it is believed that it is more likely that it is not well suited to quantify the range of WM capacity of children in general, rather than a problem with the normal distribution, and no transformation for this measure was utilized.

Two outliers were identified on a boxplot of WASI-2 Vocabulary data on either tail of the distribution, and two outliers were identified on a boxplot of WISC-IV Digit Span LDSB data on either tail of the distribution. Three outliers were identified on the AMWA-2 VSWM task (two on the right tail and one on the left tail). Two outliers were identified on the VWM change detection task at either end of the distribution. One outlier was identified on the Conners 3 Inattentive subscale on the right tail of the distribution. For all data, identified outliers were within the acceptable range of scores for each standardized measure, and therefore were not deleted. Table 5 contains normality statistics for all child measures.
Table 5.

Normality of Distribution for All Child Measures

<table>
<thead>
<tr>
<th>Measure</th>
<th>Skew</th>
<th>Kurtosis</th>
<th>Shapiro-Wilks</th>
</tr>
</thead>
<tbody>
<tr>
<td>WASI-2 Vocabulary</td>
<td>-.08</td>
<td>.27</td>
<td>.97</td>
</tr>
<tr>
<td>WASI-2 Matrix Reasoning</td>
<td>.15</td>
<td>-.70</td>
<td>.98</td>
</tr>
<tr>
<td>WASI-2 FSIQ</td>
<td>-.02</td>
<td>-1.02</td>
<td>.97</td>
</tr>
<tr>
<td>WISC-IV Digit Span</td>
<td>.31</td>
<td>-.43</td>
<td>.97</td>
</tr>
<tr>
<td>WISC-IV Letter Number Seq.</td>
<td>.25</td>
<td>-.26</td>
<td>.97</td>
</tr>
<tr>
<td>WISC-IV Arithmetic</td>
<td>.26</td>
<td>-.68</td>
<td>.96</td>
</tr>
<tr>
<td>WISC-IV WMI</td>
<td>.44</td>
<td>-.07</td>
<td>.97</td>
</tr>
<tr>
<td>WISC-IV Digit Span LDSF</td>
<td>.58</td>
<td>.47</td>
<td>.89**</td>
</tr>
<tr>
<td>WISC-IV Digit Span LDSB</td>
<td>-.11</td>
<td>.45</td>
<td>.92*</td>
</tr>
<tr>
<td>WISC-IV Digit Span Forward</td>
<td>.46</td>
<td>-.43</td>
<td>.95*</td>
</tr>
<tr>
<td>WISC-IV Digit Span Backward</td>
<td>-.00</td>
<td>-.29</td>
<td>.97</td>
</tr>
<tr>
<td>RCMAS-2</td>
<td>.06</td>
<td>-.36</td>
<td>.98</td>
</tr>
<tr>
<td>CTOPP-2 Phonological Awareness</td>
<td>.00</td>
<td>-.86</td>
<td>.96</td>
</tr>
<tr>
<td>AWMA VWM</td>
<td>.53</td>
<td>-.13</td>
<td>.97</td>
</tr>
<tr>
<td>AWMA VSWM</td>
<td>.40</td>
<td>-.19</td>
<td>.96</td>
</tr>
<tr>
<td>Conners 3 Inattention</td>
<td>.68</td>
<td>-.55</td>
<td>.92*</td>
</tr>
<tr>
<td>Conners 3 Hyperactive Impulsive</td>
<td>.71</td>
<td>-.22</td>
<td>.93*</td>
</tr>
<tr>
<td>Conners 3 ADHD Inattention</td>
<td>.61</td>
<td>-.65</td>
<td>.93*</td>
</tr>
<tr>
<td>Conners 3 ADHD Hyperactive Impulsive</td>
<td>.62</td>
<td>-.27</td>
<td>.95*</td>
</tr>
<tr>
<td>Conners 3 ADHD Inattentive Symptoms</td>
<td>.94</td>
<td>-.76</td>
<td>.75**</td>
</tr>
<tr>
<td>Conners 3 ADHD Hyperactive Impulsive Symptoms</td>
<td>.78</td>
<td>.50</td>
<td>.91**</td>
</tr>
<tr>
<td>Conners 3 ADHD Combined Symptoms</td>
<td>.70</td>
<td>-.73</td>
<td>.88**</td>
</tr>
<tr>
<td>Computerized Change Detection: VWM</td>
<td>.19</td>
<td>1.43</td>
<td>.29</td>
</tr>
<tr>
<td>Computerized Change Detection: VSWM</td>
<td>-.18</td>
<td>-.66</td>
<td>.22</td>
</tr>
</tbody>
</table>

Notes: * = p < .05; ** = p < .001
Table 6 contains normality statistics for all adult measures. As these measures were utilized to characterize the sample, but are not utilized in analyses, with the exception of change-detection WM tasks, these results are not discussed in detail in the text. In general, although skew and kurtosis were somewhat larger than 1.0 for some measures (WASI-2 Matrix Reasoning and Vocabulary subscales, CAARS Hyperactivity/Restlessness, Impulsivity/Emotional Lability subscales, and DSM-IV ADHD Symptom Total subscales, and BAI), the most notable deviations from normality as assessed by these scores were the computerized change detection tasks (VSWM Skewness = -1.24, Kurtosis = 4.13; VWM Kurtosis = -1.46). Shapiro-Wilks was significant only for the VSWM measure, and three outliers were identified (one on the right tail, and 2 on the left tail of the distribution), however these were within an acceptable range of scores on the measure. As these measures were not utilized in analyses, with the exception of change-detection tasks, no transformations were utilized.
<table>
<thead>
<tr>
<th>Measure</th>
<th>Skew</th>
<th>Kurtosis</th>
<th>Shapiro-Wilks</th>
</tr>
</thead>
<tbody>
<tr>
<td>WASI-2 Vocabulary</td>
<td>-0.32</td>
<td>1.28</td>
<td>0.97</td>
</tr>
<tr>
<td>WASI-2 Matrix Reasoning</td>
<td>1.17</td>
<td>1.35</td>
<td>0.91</td>
</tr>
<tr>
<td>WASI-2 FSIQ</td>
<td>-0.50</td>
<td>-0.01</td>
<td>0.96</td>
</tr>
<tr>
<td>CAARS: Inattention/Memory Problems</td>
<td>-0.20</td>
<td>0.04</td>
<td>0.95</td>
</tr>
<tr>
<td>CAARS: Hyperactivity/Restlessness</td>
<td>1.01</td>
<td>1.26</td>
<td>0.94</td>
</tr>
<tr>
<td>CAARS: Impulsivity/Emotional Lability</td>
<td>0.68</td>
<td>-0.39</td>
<td>0.94</td>
</tr>
<tr>
<td>CAARS: DSM-IV Inattentive Symptoms</td>
<td>0.40</td>
<td>-0.15</td>
<td>0.96</td>
</tr>
<tr>
<td>CAARS: DSM-IV Hyperactive/Impulsive Symptoms</td>
<td>0.43</td>
<td>-0.37</td>
<td>0.95</td>
</tr>
<tr>
<td>CAARS: DSM-IV ADHD Symptom Total</td>
<td>1.09</td>
<td>0.99</td>
<td>0.90</td>
</tr>
<tr>
<td>CAARS: ADHD Index</td>
<td>0.88</td>
<td>0.92</td>
<td>0.94</td>
</tr>
<tr>
<td>CAARS: Problems with Self-Concept</td>
<td>-0.12</td>
<td>-0.92</td>
<td>0.95</td>
</tr>
<tr>
<td>BAI</td>
<td>1.35</td>
<td>1.64</td>
<td>0.84</td>
</tr>
<tr>
<td>Computerized Change Detection: VWM</td>
<td>-0.09</td>
<td>-1.46</td>
<td>0.35</td>
</tr>
<tr>
<td>Computerized Change Detection: VSWM</td>
<td>-1.24</td>
<td>4.13</td>
<td>0.01*</td>
</tr>
</tbody>
</table>

Notes: * = p < .05; ** = p < .001

**Descriptive statistics of child sample.** Descriptive statistics (M, SD, frequencies, ranges, and percentages) were computed for all psychological and neuropsychological variables (see Table 7). To further characterize the sample, the measures are also described qualitatively in the following text.
### Table 7.
**Descriptives of Standardized Child Assessment Measures**

<table>
<thead>
<tr>
<th>Domain</th>
<th>Test</th>
<th>Standard Score M (SD)</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intelligence</td>
<td>WASI-II: Vocabulary(^c)</td>
<td>54 (7.65)</td>
<td>36-75</td>
</tr>
<tr>
<td></td>
<td>WASI-II: Matrix Reasoning(^c)</td>
<td>50 (9.12)</td>
<td>32-69</td>
</tr>
<tr>
<td></td>
<td>WASI-II: FSIQ-2(^a)</td>
<td>102 (11.83)</td>
<td>80-125</td>
</tr>
<tr>
<td>Working Memory</td>
<td>WISC-IV: WMI(^a)</td>
<td>97 (13.47)</td>
<td>71-132</td>
</tr>
<tr>
<td></td>
<td>WISC-IV: Digit Span(^b)</td>
<td>10 (2.99)</td>
<td>4-16</td>
</tr>
<tr>
<td></td>
<td>WISC-IV: Letter Number Seq.(^b)</td>
<td>9 (2.75)</td>
<td>4-15</td>
</tr>
<tr>
<td></td>
<td>WISC-IV: Arithmetic</td>
<td>11 (3.47)</td>
<td>5-18</td>
</tr>
<tr>
<td></td>
<td>WISC-IV: Digit Span Forward(^b)</td>
<td>9 (2.75)</td>
<td>5-16</td>
</tr>
<tr>
<td></td>
<td>WISC-IV: Digit Span Backward(^b)</td>
<td>10 (3.31)</td>
<td>3-17</td>
</tr>
<tr>
<td></td>
<td>AWMA-VWM Listening Recall(^a)</td>
<td>97 (17.51)</td>
<td>68-141</td>
</tr>
<tr>
<td></td>
<td>AWMA-VWM Listening Recall Processing(^a)</td>
<td>97 (16.68)</td>
<td>73-137</td>
</tr>
<tr>
<td></td>
<td>AWMA-VSWM Spatial Recall(^a)</td>
<td>104 (15.49)</td>
<td>73-137</td>
</tr>
<tr>
<td></td>
<td>AWMA-VSWM Spatial Recall Processing(^a)</td>
<td>104 (15.25)</td>
<td>80-137</td>
</tr>
<tr>
<td></td>
<td>Change Detection: VSWM(^d)</td>
<td>1.87 (.96)</td>
<td>-14-3.41</td>
</tr>
<tr>
<td></td>
<td>Change Detection: VWM(^d)</td>
<td>1.22 (1.06)</td>
<td>-1.86-4.18</td>
</tr>
<tr>
<td>Achievement</td>
<td>CTOPP-2: Elision(^b)</td>
<td>9 (2.64)</td>
<td>5-15</td>
</tr>
<tr>
<td>Test</td>
<td>Score (Mean)</td>
<td>Range</td>
<td></td>
</tr>
<tr>
<td>-------------------------------------------</td>
<td>--------------</td>
<td>--------</td>
<td></td>
</tr>
<tr>
<td>CTOPP-2: Blending Words&lt;sup&gt;b&lt;/sup&gt;</td>
<td>9 (2.64)</td>
<td>4-14</td>
<td></td>
</tr>
<tr>
<td>CTOPP-2: Phoneme Isolation&lt;sup&gt;b&lt;/sup&gt;</td>
<td>9 (3.58)</td>
<td>3-23</td>
<td></td>
</tr>
<tr>
<td>CTOPP-2: Phonological Awareness Composite&lt;sup&gt;c&lt;/sup&gt;</td>
<td>93 (15.06)</td>
<td>67-122</td>
<td></td>
</tr>
<tr>
<td><strong>ADHD Symptoms</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conners 3-P: Inattention&lt;sup&gt;c&lt;/sup&gt;</td>
<td>56 (13.55)</td>
<td>38-88</td>
<td></td>
</tr>
<tr>
<td>Conners 3-P: Hyperactivity/Impulsivity&lt;sup&gt;c&lt;/sup&gt;</td>
<td>57 (14.14)</td>
<td>37-90</td>
<td></td>
</tr>
<tr>
<td>Conners 3-P: ADHD Inattention&lt;sup&gt;c&lt;/sup&gt;</td>
<td>54 (13.33)</td>
<td>35-84</td>
<td></td>
</tr>
<tr>
<td>Conners 3-P: ADHD Hyperactive/Impulsive&lt;sup&gt;c&lt;/sup&gt;</td>
<td>57 (12.75)</td>
<td>37-87</td>
<td></td>
</tr>
<tr>
<td>Conners 3-P: ADHD Inattentive Symptom Count</td>
<td>2.4 (3.06)</td>
<td>0-9</td>
<td></td>
</tr>
<tr>
<td>Conners 3-P: ADHD Hyperactive/Impulsive Symptom Count</td>
<td>2.5 (2.00)</td>
<td>0-8</td>
<td></td>
</tr>
<tr>
<td>Conners 3-P: ADHD Combined Symptom Count</td>
<td>4.9 (4.48)</td>
<td>0-16</td>
<td></td>
</tr>
<tr>
<td><strong>Other Psychological/Behavioral Symptoms</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conners 3-P: Learning Problems&lt;sup&gt;c&lt;/sup&gt;</td>
<td>51 (13.90)</td>
<td>38-90</td>
<td></td>
</tr>
<tr>
<td>Conners 3-P: Executive Functioning&lt;sup&gt;c&lt;/sup&gt;</td>
<td>52 (11.89)</td>
<td>35-80</td>
<td></td>
</tr>
<tr>
<td>Conners 3-P: Defiance/Aggression&lt;sup&gt;c&lt;/sup&gt;</td>
<td>56 (13.37)</td>
<td>42-90</td>
<td></td>
</tr>
<tr>
<td>Conners 3-P: Peer Relations&lt;sup&gt;c&lt;/sup&gt;</td>
<td>52 (12.79)</td>
<td>41-90</td>
<td></td>
</tr>
<tr>
<td>Conners 3-P: Conduct Disorder&lt;sup&gt;c&lt;/sup&gt;</td>
<td>53 (9.61)</td>
<td>43-90</td>
<td></td>
</tr>
<tr>
<td>Conners 3-P: Oppositional Defiant Disorder&lt;sup&gt;c&lt;/sup&gt;</td>
<td>57 (14.45)</td>
<td>0-90</td>
<td></td>
</tr>
<tr>
<td>Conners 3-P: Global Index - Emotional Lability&lt;sup&gt;c&lt;/sup&gt;</td>
<td>56 (11.12)</td>
<td>42-87</td>
<td></td>
</tr>
</tbody>
</table>
Conners 3-P: Global Index-Restless-Impulsivity\(^c\)  
56 (16.57)  2-90

Conners 3-P: Global Index Total\(^c\)  
58 (13.95)  39-90

RCMAS-2 Short  
47 (7.33)  33-65

**Notes:**  
\(^a\) Standard score \(M(SD) = 100 (15)\).  
\(^b\) Standard score \(M(SD) = 10 (3)\).  
\(^c\) T-score \(M(SD) = 50 (10)\).  
\(^d\) Luck and Vogel (1997) \(M(SD)\) WM capacity.

**Intelligence.** The mean Full Scale IQ as measured by the WASI-II two-subtest form was 102, in the Average range. Standard scores ranged from 80 to 125, indicating participants ranged from Low Average to Superior intelligence. Similarly, both the Vocabulary and Matrix Reasoning subtest mean T-scores were in the Average range. However, T-scores ranged from 36-75 and 32-69 respectively, indicating participant performance ranged from Borderline to Very Superior.

**Working memory.** Although mean scores for all standardized WM measures were in the Average range, there was significant variability within measures. Specifically, performance on the WISC-IV WMI ranged from Borderline to Very Superior, and 8% of the sample scored below a standard score of 80. Performance on the WISC-IV Digit Span, Digit Span Forward, and Arithmetic subtests ranged from Borderline to Very Superior. Performance on WISC-IV Letter Number Sequencing subtest ranged from Borderline to Superior, and WISC-IV Digit Span Backward subtest ranged from Moderately Impaired to Very Superior. Across WISC-IV WM subtests, 6% of the sample scored below a scaled score of six (Low Average range).

On the AWMA-2, VWM recall ranged from Impaired to Very Superior, and 20% of the sample scored below a standard score of 80. VSWM recall ranged from Borderline to Very Superior, and only 2% scored below a standard score of 80.
Phonological awareness. Although mean scores of the Phonological Awareness Composite and subtest scores were in the average range (SS = 93 and ss = 9, respectively), participant scores evidenced variability. Despite no reported diagnosis of a specific learning disorder in any participant, scores on the Phonological Awareness Composite ranged from Mildly Impaired to Superior, with 20% of the sample scoring below a standard score of 80.

ADHD symptoms. Although mean scores on Conners 3P Inattentive and Hyperactivity/Impulsivity symptom subscales as well as DSM-5 ADHD Inattention and ADHD Hyperactivity/Impulsivity scales were in the average range (T-score range = 54-57), significant variability was again noted within subscales. On both the Inattention and Hyperactivity/Impulsivity subscales, 8% of the sample had Elevated scores ($t = 65-69$) indicating parents had more concerns than typically reported, and 18% of the sample had very elevated scores ($t \geq 70$), indicating parents had many more concerns than typically reported. On the DSM-5 ADHD Inattention subscale, 2% of the sample had Elevated scores and 22% had Very Elevated scores. On the DSM-5 Hyperactivity/Impulsivity subscale, 6% of the sample had Elevated scores, and 20% had Very Elevated scores. On the Global Index Restless/Impulsivity, 9% and 22% of the sample had Elevated and Very Elevated scores, respectively.

Other psychological/behavioral symptoms. Sample means for other psychological/behavioral symptoms were all in the average range. On the Conners-3P, 2 and 14% of the sample had Elevated and Very Elevated Learning Problems scores, respectively. With respect to Executive Functioning scores, 6 and 10% of the sample had Elevated and Very Elevated scores, respectively. With respect to Defiance/Aggress, 2 and 18% of the sample had Elevated and Very Elevated scores, respectively. With respect to Peer Relations, 8 and 10% of the sample had Elevated and Very Elevated scores, respectively. With respect to DSM-5
Conduct Disorder symptoms, 6 and 4 percent of the sample had Elevated and Very Elevated scores, respectively. With respect to DSM-5 Oppositional Defiant Disorder symptoms, 12 and 16% of the sample had Elevated and Very Elevated scores, respectively. With respect to Global Emotional Lability, 10 and 6% of the sample had Elevated and Very Elevated scores, respectively. With respect to Global Index Total, 12 and 22% of the sample had Elevated and Very scores, respectively. Finally, 2% of the sample had Moderately Problematic levels of anxiety, where as 98% of the sample had anxiety levels that were No More Problematic or Less Problematic than most individuals, and no one had Extremely Problematic levels of anxiety as classified by the RCMAS-2 short form.

**Descriptive statistics of adult sample.** Descriptive statistics ($M$, $SD$, frequencies, ranges, and percentages) were computed for all adult psychological and neuropsychological variables. As the focus of this project is on the child-related variables, and adult participants were only utilized as a developmental comparison group for change-detection WM tasks, the descriptives of the adult sample are provided in Table 8, below, but will not be discussed in the text.
Table 8.

Descriptives of Standardized Adult Assessment Measures

<table>
<thead>
<tr>
<th>Domain</th>
<th>Test</th>
<th>Standard Score $M$ (SD)</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intelligence</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>WASI-II: Vocabulary$^c$</td>
<td>53 (9.47)</td>
<td>32-72</td>
</tr>
<tr>
<td></td>
<td>WASI-II: Matrix Reasoning$^c$</td>
<td>57 (6.64)</td>
<td>48-73</td>
</tr>
<tr>
<td></td>
<td>WASI-II: FSIQ-2$^a$</td>
<td>109 (11.75)</td>
<td>83-126</td>
</tr>
<tr>
<td>Working Memory</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Change Detection: VSWM$^d$</td>
<td>3.38 (.85)</td>
<td>1.13-4.66</td>
</tr>
<tr>
<td></td>
<td>Change Detection: VWM$^d$</td>
<td>2.95 (1.11)</td>
<td>1.23-4.50</td>
</tr>
<tr>
<td>ADHD Symptoms</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>CAARS: Inattention/Memory Problems$^c$</td>
<td>47 (6.78)</td>
<td>35-59</td>
</tr>
<tr>
<td></td>
<td>CAARS: Hyperactivity/Restlessness$^c$</td>
<td>45 (7.63)</td>
<td>35-64</td>
</tr>
<tr>
<td></td>
<td>CAARS: Impulsivity/Emotional Lability$^c$</td>
<td>45 (9.56)</td>
<td>33-65</td>
</tr>
<tr>
<td></td>
<td>CAARS: DSM-IV Inattentive Symptoms$^c$</td>
<td>58 (13.80)</td>
<td>39-63</td>
</tr>
<tr>
<td></td>
<td>CAARS: DSM-IV Hyperactive/Impulsive Symptoms$^c$</td>
<td>48 (8.16)</td>
<td>36-64</td>
</tr>
<tr>
<td></td>
<td>CAARS: DSM-IV ADHD Symptoms Total$^c$</td>
<td>54 (11.50)</td>
<td>41-82</td>
</tr>
<tr>
<td></td>
<td>CAARS: ADHD Index$^c$</td>
<td>39 (5.56)</td>
<td>31-52</td>
</tr>
<tr>
<td>Other Symptoms</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>CAARS Problems with Self-Concept$^c$</td>
<td>51 (7.60)</td>
<td>39-63</td>
</tr>
<tr>
<td></td>
<td>BAI Total</td>
<td>10 (7.00)</td>
<td>4-28</td>
</tr>
</tbody>
</table>

Notes: $^a$ Standard score $M$(SD) = 100 (15). $^b$ Standard score $M$(SD) = 10 (3). $^c$ T-score $M$(SD) = 50 (10). $^d$ Luck and Vogel (1997) $M$(SD) WM capacity.
Correlations among child WM Measures, ADHD symptoms, and other neuro-psychological variables. Prior to conducting stepwise multiple regression analyses to investigate study hypotheses, correlations between ADHD and WM measures and other neuropsychological variables were reviewed in order to assess for potential multicollinearity. These are listed below in Table 9. Correlations between ADHD and WM measures will be provided later, in the context of study hypotheses. Participant FSIQ as measured by the WASI-II two subtest forms was significantly positively correlated with all WM measures ($r = .34$ to $.66$, $p < .05$ to .01), with the exception of computerized change-detection tasks. It was also significantly negatively correlated with Inattention ($r = -.33$, $p < .05$), ADHD Inattention ($r = -.34$, $p < .05$), and ADHD Hyperactive/Impulsive Symptoms ($r = -.32$, $p < .05$). Anxiety as measured by the RCMAS-2 short form was only significantly negatively correlated with ADHD Inattentive Symptoms ($r = -.31$, $p < .05$), and significantly positively correlated with the VSWM change-detection task ($r = .29$, $p < .05$). With the exception of the computerized change-detection tasks, CTOPP-2 Phonological Awareness was significantly positively correlated with all WM measures ($r = .50$ to .56, $p < .01$), but it was not significantly correlated with any ADHD symptom scales.
Table 9.
Correlations Among Child WM Measures, ADHD Symptoms, and Other Neuropsychological Variables

<table>
<thead>
<tr>
<th></th>
<th>FSIQ-2</th>
<th>Anxiety</th>
<th>Phonological Awareness</th>
</tr>
</thead>
<tbody>
<tr>
<td>WISC-IV WMI</td>
<td>.66**</td>
<td>.09</td>
<td>.56**</td>
</tr>
<tr>
<td>WISC-IV Digit Span</td>
<td>.55**</td>
<td>.06</td>
<td>.47**</td>
</tr>
<tr>
<td>WISC-IV Letter Number Seq.</td>
<td>.57**</td>
<td>.10</td>
<td>.47**</td>
</tr>
<tr>
<td>WISC-IV Arithmetic</td>
<td>.60**</td>
<td>.03</td>
<td>.44**</td>
</tr>
<tr>
<td>WISC-IV Digit Span Forward</td>
<td>.54**</td>
<td>-.03</td>
<td>.41**</td>
</tr>
<tr>
<td>WISC-IV Digit Span Backward</td>
<td>.36*</td>
<td>.17</td>
<td>.43**</td>
</tr>
<tr>
<td>AWMA-2 VWM</td>
<td>.42**</td>
<td>-.02</td>
<td>.43**</td>
</tr>
<tr>
<td>AWMA-2 VSWM</td>
<td>.34*</td>
<td>.20</td>
<td>.44**</td>
</tr>
<tr>
<td>VSWM Change Detection</td>
<td>.28</td>
<td>.29*</td>
<td>-.01</td>
</tr>
<tr>
<td>VWM Change Detection</td>
<td>.19</td>
<td>.07</td>
<td>.06</td>
</tr>
<tr>
<td>Inattention</td>
<td>-.33*</td>
<td>-.13</td>
<td>-.25</td>
</tr>
<tr>
<td>Hyperactivity/Impulsivity</td>
<td>-.28</td>
<td>-.05</td>
<td>-.15</td>
</tr>
<tr>
<td>ADHD Inattention</td>
<td>-.34*</td>
<td>-.14</td>
<td>-.27</td>
</tr>
<tr>
<td>ADHD Hyperactivity/Impulsivity</td>
<td>-.25</td>
<td>.06</td>
<td>-.10</td>
</tr>
<tr>
<td>ADHD Inattentive Symptoms</td>
<td>-.19</td>
<td>-.31*</td>
<td>-.15</td>
</tr>
<tr>
<td>ADHD Hyperactive/Impulsive Symptoms</td>
<td>-.32*</td>
<td>.06</td>
<td>-.16</td>
</tr>
<tr>
<td>ADHD Combined Symptoms</td>
<td>-.27</td>
<td>-.20</td>
<td>-.16</td>
</tr>
</tbody>
</table>

Notes: *p < .05; **p < .01.
Analyses of Primary Study Hypotheses

In order to examine relationships between demographic and neuropsychological variables, as well as identify potential multicollinearity, bivariate Pearson correlation coefficients were computed among WM measures (Tables 10 & 11), between individual WM measures and ADHD symptoms (Tables 14, 15, and 16), and between other neuropsychological symptoms (e.g., FSIQ, anxiety, phonological awareness) and WM and ADHD symptoms (Table 9). Although several variables were significantly correlated, and, throughout regression equations in analyses below, variance inflation factor (VIF) and Tolerance statistics were also examined for multicollinearity. Correlations are described qualitatively below with respect to specific study hypotheses. Following examination of bivariate correlations, multivariate analyses were conducted for each of the four study aims.

Aim 1: To validate the use of computerized change-detection paradigms in neurotypical children.

Hypothesis 1: Performance of children on arrays of 1-3 items will be nearly perfect and decline systematically with set size increase from 4 to 12 items, consistent with results of Luck and Vogel (1997) in an adult sample, as theories suggest one way to accurately assess WM is by overloading the processing system (Cowan, 2000). Descriptive statistics were reviewed in order to evaluate VWM and VSWM capacity as assessed by the change-detection paradigms in child and adult samples, and an independent samples t-test of mean differences was conducted to compare mean WM capacity between groups. In the adult sample, VWM ($M = 2.95, SD = 1.11$) and VSWM ($M = 3.38, SD = .85$) capacity were similar to that reported by Luck and Vogel (1997; 3-4 items). In the child sample, VWM ($M = 1.22, SD = 1.06$) and VSWM ($M = 1.87, SD = .96$) capacities were significantly smaller than in the
adult group ($t = -5.13$ and $-5.15$ respectively, $p < .001$). Visual inspections of WM capacity between groups across elements (see Figure 6), revealed a similar pattern of performance between child and adult groups – a systematic decline in performance was notable in both VWM and VSWM with increased set-size.

**Figure 6. VSWM and VWM Mean Performance Across Elements.**

**Hypothesis 2: Age-related changes on WM measures are expected, and WM capacity is expected to increase with age, consistent with previous research (e.g., Alloway et al., 2004; Gathercole et al., 2004; Swanson, 2008).** Pearson correlation coefficients were calculated between child age and VSWM and VWM capacity as assessed by the change-detection paradigm. Age was moderately positively correlated with both mean VSWM ($r = .31, p < .05$) and VWM ($r = .33, p < .05$). A Fisher r-to-Z transformation revealed that these correlations were not significantly different ($z = -.12, p = .45$), suggesting similar age effects on two working memory measures.

**Hypothesis 3: Age-related differences between VSWM and VWM capacity are expected. Younger children are expected to have greater differences between VSWM and VWM than older children, consistent with Gathercole et al.’s (2004) research showing children tend to rely on VSWM until around age 6 or 7, at which time they begin to relying more on VWM.** Visual analysis of VSWM and VWM as a function of age (see Figure 7) re-
vealed both systematically increase with age. A linear regression analysis indicated the mean difference between VSWM and VWM is not significant as a function of age ($r^2 = .01, p = .52$).

![Graph]

**Figure 7.** VSWM and VWM Capacity as a Function of Age.

**Aim 2:** To investigate the relationship between WM functioning as assessed clinically with the WISC-IV and experimental measures of WM such as computerized change-detection paradigms and computerized span tasks. Bivariate correlations revealed significant positive correlations among several clinical WM tasks (See Table 10). The WMI as a whole was not significantly correlated with scores on the AWMA-2 VWM task. Scores on the WISC-IV Digit Span subtest were significantly correlated with scores on both the AWMA-2 VWM task ($r = .33, p < .05$). When Digit Span Forward and Backward subtests were considered individually, scores on the Digit Span Forward task were significantly correlated with scores on the AWMA-2 VWM task ($r = .31, p < .05$), though it was not correlated with performance on the AWMA-2 VSWM task. Performance on the Digit Span Backward was significantly correlated with performance on the AWMA-2 VWM task ($r = .29, p < .05$). Scores on the WISC-IV Letter Number Sequencing subtest were not significantly correlated
with scores on the AWMA-2. The WISC-IV Arithmetic subtest scores were significantly positively correlated with AWMA-2 VWM and VSWM scores ($r = .37, p < .01, r = .44, p < .01$, respectively).

Table 10.
Correlations Among Clinical WM Measures.

<table>
<thead>
<tr>
<th></th>
<th>WISC-IV WMI</th>
<th>WISC-IV Digit Span</th>
<th>WISC-IV Letter Number Seq.</th>
<th>WISC-IV Arithmetic</th>
<th>WISC-IV Digit Span Forward</th>
<th>WISC-IV Digit Span Backward</th>
</tr>
</thead>
<tbody>
<tr>
<td>AWMA-2 VWM</td>
<td>0.23</td>
<td>.33*</td>
<td>0.05</td>
<td>.37**</td>
<td>.31*</td>
<td>.29*</td>
</tr>
<tr>
<td>AWMA-2 VSWM</td>
<td>0.22</td>
<td>0.24</td>
<td>0.13</td>
<td>.44**</td>
<td>0.15</td>
<td>0.20</td>
</tr>
</tbody>
</table>

Notes: *$p < .05$; **$p < .01$.

Bivariate correlations between the computerized change-detection paradigms and clinical WM assessments (WMI and AWMA-2) revealed that only the Arithmetic subtest and the VSWM change-detection task scores were significantly positively correlated ($r = .34, p < .05$). No other relationships approached significance (see Table 11).
Table 11.
*Correlations Between Clinical and Experimental WM Measures*

<table>
<thead>
<tr>
<th></th>
<th>VSWM Change Detection</th>
<th>VWM Change Detection</th>
</tr>
</thead>
<tbody>
<tr>
<td>AWMA-2 VWM</td>
<td>.10</td>
<td>.09</td>
</tr>
<tr>
<td>AWMA-2 VSWM</td>
<td>.21</td>
<td>.04</td>
</tr>
<tr>
<td>WISC-IV WMI</td>
<td>.15</td>
<td>.08</td>
</tr>
<tr>
<td>WISC-IV Digit Span</td>
<td>.18</td>
<td>.03</td>
</tr>
<tr>
<td>WISC-IV Letter Number Seq.</td>
<td>.09</td>
<td>.12</td>
</tr>
<tr>
<td>WISC-IV Arithmetic</td>
<td>.34*</td>
<td>.12</td>
</tr>
<tr>
<td>WISC-IV Digit Span Forward</td>
<td>.22</td>
<td>.11</td>
</tr>
<tr>
<td>WISC-IV Digit Span Backward</td>
<td>.09</td>
<td>-.07</td>
</tr>
</tbody>
</table>

*Notes:* *p < .05; **p < .01.

**Hypothesis 4:** The WISC-IV WMI and Wechsler subtests such as Digit Span and Letter-Number sequencing will account for a significant amount of variance in criterion constructs commonly utilized in WM literature (computerized change-detection paradigms and span tasks), consistent with results of Hill et al. (2010) in an adult sample. **Hypothesis 5:** The Arithmetic subtest will not add unique variance and will be excluded from the best predictor model of WM, consistent with results of Hill et al. (2010) in an adult sample.

Based on a priori hypotheses and bivariate relationships between variables, predictors were chosen for stepwise regression analyses. Bivariate correlations between age and CTOPP-2 PA Composite and criterion variables were also examined. When significant relationships were found, these were entered as additional predictors in regression equations.
WISC-IV and change-detection tasks. In the first simple regression, the VSWM change-detection task was the criterion variable and the WISC-IV Arithmetic subtest was the predictor variable, as this was the only WISC-IV WM subtest with significant or near-significant correlation to the VSWM task. Arithmetic significantly accounted for 12% of the variance in VSWM scores. As anxiety as measured by the RCMAS was also significantly correlated with VSWM scores, a step-wise multiple regression utilizing both Arithmetic and the RCMAS-2 scores as the predictor variables, and VSWM as the criterion. Both the RCMAS and Arithmetic were significant predictors of VSWM as assessed by the change-detection task, accounting for 20% of the variance ($p < .01$). See Table 12 for full results. No regression analyses utilizing the VWM task as a criterion variable were conducted, as it was not significantly or near-significantly correlated with any clinical WM tasks.

<table>
<thead>
<tr>
<th>Model 1</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>.87</td>
<td>.43</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Arithmetic</td>
<td>.09</td>
<td>.04</td>
<td>.34</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Model 2</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>-.82</td>
<td>.91</td>
<td></td>
</tr>
<tr>
<td>Arithmetic</td>
<td>.09</td>
<td>.04</td>
<td>.34</td>
</tr>
<tr>
<td>RCMAS</td>
<td>.04</td>
<td>.02</td>
<td>.28</td>
</tr>
</tbody>
</table>

WISC-IV and AWMA-2. In the next regression analysis, WISC-IV WM subtests sig-
nificantly correlated (Digit Span, Arithmetic) with AWMA-2 VWM were entered as predictor variables, and the AWMA-2 VWM was the criterion variable. Arithmetic was the only significant predictor of AWMA-2 VWM, accounting for 14% of the variance (p < .01). Additionally, as both the Digit Span Forward and Digit Span Backward components of Digit Span were individually significantly correlated with AWMA-2 VWM, a stepwise regression analysis with these individually entered as predictors in place of Digit Span was conducted. Results were unchanged, and Arithmetic continued to be the only significant predictor of AWMA-2 VWM. See Table 13 for full results.

Table 13.

Simple and Stepwise Multiple Regression Analyses Predicting AWMA-2 VWM

<table>
<thead>
<tr>
<th></th>
<th>B</th>
<th>SE (B)</th>
<th>R²</th>
<th>β</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>AWMA-2 VWM Model&lt;sup&gt;a&lt;/sup&gt;</td>
<td>.14</td>
<td></td>
<td>.009</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>76.63</td>
<td>7.71</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Arithmetic</td>
<td>1.85</td>
<td>.68</td>
<td>.37</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>B</th>
<th>SE (B)</th>
<th>R²</th>
<th>β</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>AWMA-2 VWM Model with Additional Predictors&lt;sup&gt;b&lt;/sup&gt;</td>
<td>.18</td>
<td></td>
<td>.002</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>50.61</td>
<td>14.32</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CTOPP-2 PA Comp.</td>
<td>.50</td>
<td>.15</td>
<td>.43</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes: <sup>a</sup>Predictors: Digit Span, Arithmetic, <sup>b</sup>Predictors: Arithmetic, CTOPP-2 PA Comp

Next, a simple regression with, Arithmetic, the only WISC-IV subtest significantly correlated with AWMA-2 VSWM, as the predictor variable, and AWMA-2 VSWM was the
criterion variable. Arithmetic did significantly predict AWMA-2 VSWM performance, accounting for 19% of the variance \( (p < .01; \) See Table 14).

Table 14.

*Simple and Stepwise Multiple Regression Analyses Predicting AWMA-2 VSWM*

<table>
<thead>
<tr>
<th></th>
<th>( B )</th>
<th>( SE (B) )</th>
<th>( R^2 )</th>
<th>( \beta )</th>
<th>( p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>AWMA-2 VSWM Model(^a)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>82.59</td>
<td>6.64</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Arithmetic</td>
<td>1.98</td>
<td>.59</td>
<td>.44</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AWMA-2 VSWM Model with Additional Predictor(^b)</td>
<td>( .24 )</td>
<td>( .001 )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>59.67</td>
<td>12.26</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Arithmetic</td>
<td>1.40</td>
<td>.63</td>
<td>.31</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CTOPP-2 PA Comp</td>
<td>.31</td>
<td>.14</td>
<td>.30</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Notes:* \(^a\)Predictor: Arithmetic, \(^b\)Predictor: Arithmetic, CTOPP-2 PA Comp

Given that both AWMA-2 VWM and VSWM were significantly positively correlated with CTOPP-2 PA Composite \( (r = .43 \& .44, p < .01, \) respectively), follow-up stepwise multiple regression analyses with the CTOPP-2 PA Composite entered as an additional predictor variable were conducted. The CTOPP-2 PA Composite became the only significant predictor of AMWA-2 VWM, accounting for 18% of the variance \( (p < .01). \) Both the CTOPP-2 PA Composite and Arithmetic subtest were significant predictors of AWMA-2 VSWM, accounting for 24% of the variance \( (p = .001). \) See Table 13 and 14 above for full regression results.
Based on these results, Hypothesis 4 was not supported, as Letter-Number sequencing was not significantly correlated with WM as assessed by change detection tasks or the AWMA-2, and Digit Span did not significantly predict VWM or VSWM as assessed by the AWMA-2. Hypothesis 5 was also not supported, as the Arithmetic subtest was the only significant predictor of WM as assessed by both the computerized VSWM change detection task and the AWMA-2.

**Hypothesis 6: Addition of subtests outside of those that currently make up the WMI may be able to account for additional variance in WM by accounting for executive attention functions and controlled retrieval of items from secondary memory. Specifically, Vocabulary and Matrix Reasoning will account for additional unique variance in the WM construct, consistent to results of Hill et al. (2010) in an adult sample.** Neither the Vocabulary nor the Matrix Reasoning subtest were significantly or near-significantly correlated with either computerized change-detection task, so analyses with these as additional predictor variables of performance on computerized change detection tasks were not conducted. However, both Vocabulary and Matrix Reasoning subtest scores were significantly correlated with AWMA-2 VWM scores ($r = .31 & .36, p < .05$, respectively), so a follow-up stepwise multiple regression analysis was conducted with the addition of these subtests as predictors (All Predictors: Vocabulary, Matrix Reasoning, Arithmetic, Digit Span). Only Vocabulary was significantly correlated with AWMA-2 VSWM ($r = .29, p < .05$); therefore, it was included as an additional predictor variable (All Predictors: Vocabulary, Arithmetic). In both models, Arithmetic continued to be the only significant predictor of AWMA-2 WM. Follow-up regression analyses substituting Digit Forward and Digit Backward for Digit Span, as well as including CTOPP-2 PA Composite as a covariate also remained unchanged from initial
AMWA-2 WM models.

As neither Vocabulary nor Matrix Reasoning subtests were significantly correlated with computerized change-detection tasks, and inclusion of Vocabulary or Matrix Reasoning did not account for additional unique variance in the WM construct as assessed by the AW-MA-2, Hypothesis 6 was not supported.

Aim 3: To examine the phenotypic features of ADHD (hyperactivity, impulsivity, and inattention) in children as measured by the Conners-3 ADHD Rating Scale and their relationship to WM functioning when continuous ADHD symptoms versus categorical ADHD classification is used.

Hypothesis 7: WM capacity will be related to number of symptoms of ADHD in the domains of hyperactivity, impulsivity, and inattention. Higher WM capacity will be related to fewer symptoms, whereas lower WM capacity will be related to a higher number of symptoms. WISC-IV WM measures revealed significant negative correlations with several ADHD subscales of the Conners 3-P. Specifically, the Inattention subscale was significantly correlated with the WMI, as well as all subtests of the WMI ($r = -.35$ to $-.44$, $p < .05$ to .01), with the exception of Letter Number Sequencing. The ADHD Inattention subscale was also significantly correlated with the WMI and all subtests ($r = -.36$ to $-.44$, $p < .01$), again with the exception of the Letter Number Sequencing subtest, as well as the Digit Span Forward component of the Digit Span subtest. Neither the Hyperactivity/Impulsivity subscale nor the ADHD Hyperactivity/Impulsivity subscales were significantly correlated with the WMI or subtests. ADHD Inattentive Symptoms and Combined symptoms significantly correlated with the WMI ($r = -.35$ & $r = -.31$, $p < .05$, respectively), Digit Span ($r = -.30$ & $-.28$, $p < .05$, respectively), and Digit Span Forward ($r = -.31$, $p < .05$). ADHD Hyperactive/Impulsive
Symptoms was only significantly correlated with the Arithmetic subtest \((r = -.28, p < .05)\).

See Table 15 below for full results. In general, these results seem to indicate the inattentive symptoms of ADHD are more closely related to WM functioning as assessed by the WISC-IV. Moreover, the Backward Digit Span component of the Digit Span subtest appears to bedriving significant relationships between the subtest as a whole and ADHD symptoms.

Table 15.

*Correlations Among WISC-IV WM Measures and ADHD Symptoms*

<table>
<thead>
<tr>
<th></th>
<th>WMI Digit Span</th>
<th>Letter Number Seq.</th>
<th>Arithmetic</th>
<th>Digit Span Forward</th>
<th>Digit Span Backward</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inattention</td>
<td>-.35*</td>
<td>-.38**</td>
<td>-.19</td>
<td>-.44**</td>
<td>-.38*</td>
</tr>
<tr>
<td>Hyperactivity/Impulsivity</td>
<td>-.24</td>
<td>-.19</td>
<td>-.20</td>
<td>-.20</td>
<td>-.14</td>
</tr>
<tr>
<td>ADHD Inattention</td>
<td>-.39**</td>
<td>-.37**</td>
<td>-.27</td>
<td>-.36**</td>
<td>-.24</td>
</tr>
<tr>
<td>ADHD Hyperactivity/Impulsivity</td>
<td>-.22</td>
<td>-.16</td>
<td>-.20</td>
<td>-.20</td>
<td>-.14</td>
</tr>
<tr>
<td>ADHD Inattentive Symptoms</td>
<td>-.35*</td>
<td>-.30*</td>
<td>-.27</td>
<td>-.20</td>
<td>-.20</td>
</tr>
<tr>
<td>ADHD Hyperactive/Impulsive Symptoms</td>
<td>-.18</td>
<td>-.18</td>
<td>-.11</td>
<td>-.28*</td>
<td>-.15</td>
</tr>
<tr>
<td>ADHD Combined Symptoms</td>
<td>-.31*</td>
<td>-.28*</td>
<td>-.23</td>
<td>-.26</td>
<td>-.20</td>
</tr>
</tbody>
</table>

Notes: *p < .05; **p < .01.

No significant correlations were found between computerized change-detection tasks and ADHD symptoms (see Table 16). However, the correlation between the Inattention subscale and VSWM as assessed by the computerized change-detection task \((r = -.28, p = .06),\)
as well as the ADHD combined symptom count and the VSWM computerized change-detection task \( (r = -.26, p = .08) \) approached significance.

Table 16.

<p>| Correlations Among Computerized Change-Detection Tasks and ADHD Symptoms |</p>
<table>
<thead>
<tr>
<th>VSWM</th>
<th>VWM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inattention</td>
<td>-.28</td>
</tr>
<tr>
<td>Hyperactivity/Impulsivity</td>
<td>-.14</td>
</tr>
<tr>
<td>ADHD Inattention</td>
<td>-.25</td>
</tr>
<tr>
<td>ADHD Hyperactivity/Impulsivity</td>
<td>-.10</td>
</tr>
<tr>
<td>ADHD Inattentive Symptoms</td>
<td>-.23</td>
</tr>
<tr>
<td>ADHD Hyperactive/Impulsive Symptoms</td>
<td>-.21</td>
</tr>
<tr>
<td>ADHD Combined Symptoms</td>
<td>-.26</td>
</tr>
</tbody>
</table>

*Notes: *p < .05; **p < .01.*

The AWMA-2 only demonstrated a few significant negative correlations with ADHD symptoms. The VSWM subtest was significantly correlated with Inattention \( (r = -.32, p < .05) \). The VWM component was not significantly correlated with any ADHD symptom scales. Table 17, below, includes all correlations between AWMA-2 WM and ADHD symptoms.
Table 17.

Correlations Among AWMA-2 WM Measures and ADHD Symptoms

<table>
<thead>
<tr>
<th></th>
<th>VWM</th>
<th>VSWM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inattention</td>
<td>-.25</td>
<td>-.32*</td>
</tr>
<tr>
<td>Hyperactivity/Impulsivity</td>
<td>-.02</td>
<td>-.03</td>
</tr>
<tr>
<td>ADHD Inattention</td>
<td>-.21</td>
<td>-.18</td>
</tr>
<tr>
<td>ADHD Hyperactivity/Impulsivity</td>
<td>-.00</td>
<td>-.01</td>
</tr>
<tr>
<td>ADHD Inattentive Symptoms</td>
<td>-.03</td>
<td>-.02</td>
</tr>
<tr>
<td>ADHD Hyperactive/Impulsive Symptoms</td>
<td>-.25</td>
<td>-.25</td>
</tr>
<tr>
<td>ADHD Combined Symptoms</td>
<td>-.13</td>
<td>-.13</td>
</tr>
</tbody>
</table>

Notes: *p < .05; **p < .01.

**Hypothesis 8: A continuous measurement of ADHD symptoms will lead to greater classification accuracy of high versus low WM than categorical classification of ADHD.**

*In other words, WM differences may not be found across categorical classifications of ADHD. However, WM capacity measures will be related to the continuous measurement of ADHD symptoms.* Given high collinearity between the Inattention and ADHD Inattention subscales ($r = .95$), that violated assumptions of no multicollinearity necessary for a multiple regression, simple linear regressions with WMI as the criterion variable, and Inattention and
ADHD Inattention subscales of the Conners 3-P as predictor variables were used to better understand clinical measurement of WM. ADHD Hyperactivity/Impulsivity and ADHD Hyperactivity/Impulsivity were not included as predictor variables, as bivariate correlations revealed neither is significantly correlated with the WMI. The ADHD Inattention subscale significantly predicted WM as assessed by the WMI, accounting for 15% of the variance ($p < .01$). The ADHD Inattention subscale significantly predicted WM as assessed by the WMI, accounting for 12% of the variance. Next, a stepwise multiple regression analysis was conducted with the Inattention subscale, as it accounted for the most variance in WMI scores, and the CTOPP-2 PA Composite included as an additional predictor due to its significant relationship with the WMI ($r = .57, p < .001$). The Conners 3 Inattentive subscale and CTOPP-2 PH Composite were both unique predictors of WMI performance, accounting for 37% of the variance ($p < .05$). Table 18 provides full regression results.
### Table 18.

**Simple and Stepwise Multiple Regression Analyses Predicting WMI Performance**

<table>
<thead>
<tr>
<th></th>
<th>$B$</th>
<th>$SE (B)$</th>
<th>$R^2$</th>
<th>$\beta$</th>
<th>$p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>WMI Model 1&lt;sup&gt;a&lt;/sup&gt;</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>115.78</td>
<td>7.75</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inattention</td>
<td>-.34</td>
<td>.13</td>
<td>.12</td>
<td>-.34</td>
<td>.014</td>
</tr>
<tr>
<td>WMI Model 2&lt;sup&gt;b&lt;/sup&gt;</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>117.69</td>
<td>7.45</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ADHD Inattention</td>
<td>-.39</td>
<td>.13</td>
<td></td>
<td>-.39</td>
<td></td>
</tr>
<tr>
<td>WMI Model with Additional Predictors&lt;sup&gt;c&lt;/sup&gt;</td>
<td>.37</td>
<td>.037</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>70.03</td>
<td>13.46</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CTOPP-2 PA Comp.</td>
<td>.44</td>
<td>.11</td>
<td>.49</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ADHD Inattention</td>
<td>-.26</td>
<td>.12</td>
<td>-.26</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Notes:**<sup>a</sup>Predictor: Inattention, <sup>b</sup>Predictor: ADHD Inattention, <sup>c</sup>Predictor: ADHD Inattention, CTOPP-2 PA Comp.

Since the Arithmetic subtest is also a clinical measure that was significantly correlated with Inattentive and ADHD Inattentive subscales of the Conners 3, yet it is not a component of the WMI, follow-up simple regressions utilizing Arithmetic as the criterion variable and Conners-3 Inattentive and ADHD Inattention as predictor variables were conducted. The model utilizing the Conners-3 ADHD Inattention subscale as a predictor of Arithmetic was not significant. The Conners-3 Inattention subscale significantly predicted performance on the Arithmetic subtest, accounting for 19% of the variance ($p < .001$). Inclusion of the
CTOPP-2 PA Composite as an additional predictor resulted in both Conners 3 Inattentive Symptoms subscale and the CTOPP-2 PA Composite significantly predicting Arithmetic performance, accounting for 30% of the variance. See Table 19 for complete regression results.

Table 19.

*Simple and Stepwise Multiple Regression Analyses Predicting Arithmetic Performance*

<table>
<thead>
<tr>
<th></th>
<th>$B$</th>
<th>SE ($B$)</th>
<th>$R^2$</th>
<th>$\beta$</th>
<th>$p$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Arithmetic Model</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>17.08</td>
<td>1.91</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inattention</td>
<td>-.111</td>
<td>.033</td>
<td>-.44</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Arithmetic Model with Additional Predictors</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>8.26</td>
<td>3.62</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CTOPP-2 PA Comp.</td>
<td>.08</td>
<td>.03</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inattention</td>
<td>-.09</td>
<td>.03</td>
<td>-.35</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Notes:* a Predictor: Inattention, b Predictor: ADHD Inattention, CTOPP-2 PA Comp.

Stepwise multiple linear regression analyses with categorical diagnosis of ADHD Inattentive subtype, ADHD Hyperactive/Impulsive subtype, and ADHD-Combined subtype as assessed by the Conners 3 ADHD symptom indexes as predictor variables, and WMI and Arithmetic as the criterion variables were conducted. No variables were retained in the final regression models, indicating categorical diagnosis of ADHD does not predict WMI or Arithmetic performance. Therefore, Hypothesis 8 was supported, as continuous measurement
of ADHD predicted WM functioning as assessed by clinical measures, whereas categorical diagnosis did not.

**Hypothesis 9:** ADHD symptoms will be related to both verbal and visuospatial WM domains, consistent with previous research finding ADHD is related to deficit in both verbal and visuospatial domains of WM (e.g. Alloway, Rajendran, & Archibald, 2009). As previously reported (see Table 15), the correlations between VSWM as assessed by the computerized change-detection task and the Inattention subscale and \( r = -.28, p = .06 \) and the ADHD combined symptom subscale \( r = -.26, p = .08 \) approached significance. No significant correlations between ADHD subscales and VWM as assessed by the computerized change-detection task were found. Similarly, as previously reported (see Table 16) the VSWM component of the AWMA-2 was significantly negatively correlated with Inattention \( r = -.32, p < .05 \), and the VWM component was not significantly correlated with any ADHD symptom scales. Therefore, as inattentive symptoms are only related to VSWM, and hyperactive/impulsive symptoms were not related to either VSWM or VWM, this hypothesis is not supported.

**Aim 4:** To examine whether computerized change-detection paradigms can better predict the phenotypic features of children with ADHD than the WISC-IV WMI.

**Hypothesis 10:** WM as measured by change-detection tasks will result in better classification (sensitivity and specificity) of ADHD than the WMI. In other words, the WM scores in change-detection tasks will better predict ADHD than the WMI scores. Stepwise multiple regression analyses were utilized to evaluate which WISC-IV WM subtests significantly predicted each Conners-3 ADHD-related subscale. Digit Span Forward and Digit Span Backward were analyzed in place of the Digit Span subtest, as bivariate correlations revealed
they are differentially related to ADHD symptoms, consistent with previous research and a priori hypotheses. As neither anxiety as measured by the RCMAS-2 nor Phonological Awareness as measured by the CTOPP-2 were significantly correlated with ADHD symptoms, these were not entered as additional predictor variables or covariates.

*Continuous classification of ADHD.* In the first regression, Arithmetic, Digit Span Forward, and Digit Span Backward were entered as predictor variables, and Conners-3 Inattention Subscale as the criterion variable. Arithmetic was the only significant predictor, accounting for 19% of the variance ($p < .01$). A simple regression utilizing only the WMI as a whole as the predictor variable accounted for only 10% of the variance ($p = .01$). Next, Digit Span Backward and Arithmetic were entered as predictor variables, and the Conners-3 ADHD Inattention subscale as the criterion variable. Digit Span Backward was the only significant predictor, accounting for 19% of the variance. A similar model utilizing only the WMI as a predictor variable accounted for only 15% of the variance ($p < .01$). Analyses were not conducted with either the Hyperactive/Impulsivity or ADHD Hyperactivity/Impulsivity subscales, as neither were significantly correlated with WISC-IV WM subtests. See Table 20 for full results.
Table 20.

Simple and Stepwise Multiple Regression Analyses Predicting ADHD Symptoms with WISC-IV WM Tasks

<table>
<thead>
<tr>
<th></th>
<th>B</th>
<th>SE (B)</th>
<th>$R^2$</th>
<th>$\beta$</th>
<th>$p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inattention Model 1&lt;sup&gt;a&lt;/sup&gt;</td>
<td>.19</td>
<td></td>
<td></td>
<td>.002</td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>74.47</td>
<td>5.78</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Arithmetic</td>
<td>-1.70</td>
<td>.51</td>
<td></td>
<td>-.44</td>
<td></td>
</tr>
<tr>
<td>Inattention Model 2&lt;sup&gt;b&lt;/sup&gt;</td>
<td>.12</td>
<td></td>
<td></td>
<td>.014</td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>89.67</td>
<td>13.27</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WMI</td>
<td>-.34</td>
<td>.14</td>
<td></td>
<td>-.35</td>
<td></td>
</tr>
<tr>
<td>ADHD Inattention Model 1&lt;sup&gt;c&lt;/sup&gt;</td>
<td>.19</td>
<td></td>
<td></td>
<td>.002</td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>71.16</td>
<td>5.40</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Digit Span Backward</td>
<td>-1.76</td>
<td>.52</td>
<td></td>
<td>-.43</td>
<td></td>
</tr>
<tr>
<td>ADHD Inattention Model 2&lt;sup&gt;b&lt;/sup&gt;</td>
<td>.15</td>
<td></td>
<td></td>
<td>.005</td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>91.09</td>
<td>12.83</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WMI</td>
<td>-.39</td>
<td>.13</td>
<td></td>
<td>-.39</td>
<td></td>
</tr>
</tbody>
</table>

Notes: <sup>a</sup>Predictor: Arithmetic, Digit Span Forward, Digit Span Backward, <sup>b</sup>Predictor: WMI, <sup>c</sup>Predictor: Digit Span Backward, Arithmetic

As only the Conners-3 Inattention and Combined Symptom Count subscale correlations approached significance with VSWM as assessed by the change detection task, two separate multiple regression analyses were conducting using these respectively as criterion variables and VSWM change-detection scores as the predictor variable. No variables entered
were retained in either equation.

*Categorical classification of ADHD.* Receiver Operating Characteristic (ROC) curves were plotted to evaluate the classification accuracy of the WISC-IV measures for formal ADHD diagnosis. First, the WMI was utilized as the test variable, and ADHD diagnosis was used as the state variable. When interpreting the area under the ROC curve, 1 represents a perfect test, whereas .5 represents a worthless test (Tape, 2014). The area under the curve (AUC) in this model was .33. Next, the Arithmetic subtest was used as the test variable, with ADHD diagnosis as the state variable. The AUC was .26. Finally, the computerized VSWM change-detection task was utilized as the test variable, with ADHD diagnosis as the state variable. The AUC was .38. These results indicate none of the WMI, Arithmetic subtest of the WISC-IV, or VSWM change-detection tasks correctly classify individuals diagnosed with ADHD. However, it is also important to note that only 20% of the sample had a previous ADHD diagnosis, so this analysis was likely underpowered.

Next, ROC curves were calculated for categorical ADHD diagnosis as assessed by ADHD Inattentive Symptoms on the Conners-3 (i.e., 6 or more symptoms). WISC-IV WMI and WMI subtests with significant relationships to ADHD Inattentive Symptoms were utilized. Neither the WMI (AUC = .35), the Digit Span (AUC = .37), nor the Digit Span Backward (AUC = .40) correctly classified individuals meeting criteria for ADHD inattentive subtype. Neither the AWMA-2 nor the computerized change-detection tasks were used as test variables, since these did not have significant correlations with ADHD Inattentive symptoms.

A ROC curve was also calculated for categorical diagnosis as assessed by ADHD Hyperactive/Impulsive Symptoms on the Conners-3 (i.e., 6 of more symptoms). The Arithmetic subscale of the WISC-IV was the only measure with a significant relationship to the
Hyperactive/Impulsive Symptom subscale, so it was utilized as the test variable. The AUC was .33, indicating it does not correctly classify individuals with ADHD hyperactive/impulsive subtype.

Finally, ROC curves were calculated for categorical ADHD diagnosis as assessed by ADHD meeting criteria for both Inattentive and Hyperactive/Impulsive subtype on the Conners-3 (i.e., 6 or more symptoms on both inattentive and hyperactive/impulsive subscales). WISC-IV WMI and WMI subtests with significant relationships to ADHD Combined Symptoms were utilized. Neither the WMI (AUC = .33), the Digit Span (AUC = .34), nor the Digit Span Backward (AUC = .26) correctly classified individuals meeting criteria for ADHD combined subtype. Neither the AWMA-2 nor the computerized change-detection tasks were used as test variables, since these did not have significant correlations with ADHD Combined symptoms.

Overall, these results indicate, Hypothesis 10 was not supported – computerized change-detection tasks do not more accurately predict ADHD than WMI scores. Moreover, WM tasks are more useful when considering ADHD symptoms continuously than diagnosis categorically.
Chapter 8: Discussion

Summary of Findings

The current study sought to better understand the relationship between experimental and clinical measurement of the WM construct, as well as the relationship between ADHD symptoms and WM capacity. Specifically, this study had four main aims. The first was to investigate the use of computerized change-detection paradigms in children, and potentially validate their use. Second, the study was designed to explore the relationships among experimental WM tasks (computerized change-detection paradigms) and clinical measurement of WM (WISC-IV WMI and AWMA-2). Third, relationships between phenotypic symptoms of ADHD (inattention, impulsivity, and hyperactivity) and WM were evaluated. Finally, this study sought to evaluate whether experimental paradigms can more accurately predict phenotypic features of WM than clinical measures. Of the proposed hypotheses, several were found to be partially supported, while others were rejected. A detailed summary of findings is discussed next.

Aim 1: Validation of computerized change-detection paradigms. Results of adult and child samples were first compared to results reported by Luck and Vogel (1997), and then to one another. The WM capacity within the adult sample was consistent with that reported by Luck and Vogel (1997) in both VWM and VSWM, indicating the change-detection paradigm used in the current study is likely eliciting the same construct as that of Luck and Vogel (1997). Moreover, these results are similar with current theories of WM that indicate WM capacity ranges from three to four chunks, and one of the most effective ways to measure WM capacity is to overload the processing system (Cowan, 2000).
Within the child sample, mean VWM and VSWM capacity ranged from 1 to 2 and was significantly lower than adult capacity. Although studies suggest the structural organization and ability to assess WM components is in place as young as four years old and remains consistent throughout childhood years (Alloway et al., 2006; Gathercole et al., 2004), results of the current study seem to indicate computerized change-detection paradigms are not effectively eliciting the WM construct in children. Notably, visual inspection of the patterns between child and adult groups were similar—with increased set size, both VSWM and VWM capacity systematically decreased, and VSWM capacity generally remained higher than VWM across set sizes. Therefore, rather than suggesting computerized change-detection tasks do not elicit the WM construct in children, current results seem to support developmental variance in WM components—that is, although the component parts and structure of WM may be in place, developmental change in the form of increases in WM capacity occur through adolescence (Gathercole et al., 2004). Supporting this, bivariate correlations revealed both VSWM and VWM increased with age. Moreover, the bivariate relationships between age and VSWM, and age and VWM were similar, and a linear regression analysis revealed average difference between VSWM and VWM are not significant as a function of age. Together, these results indicate increases in VSWM and VWM are similar to one another across age. These results are consistent with previous research indicating the strengths of relationships between subcomponents of WM (VS, PH, CE) remain similar through approximately age six to adolescence (Gathercole et al., 2004). As the frontal lobe is the principal neuroanatomical area associated with the CE, and it continues to develop throughout childhood and adolescence, and into adulthood (approximately 26 years-old; Nelson, 1995, 2000), the current results may suggest development of and increased efficiency of processing within the
CE accounts for increased of both VSWM and VSM capacity with age (Gathercole et al., 2004). This finding also fits with the theoretical perspective that WM capacity is best understood by a domain-general component, that is, activation of the CE differentiates WM from short-term memory, and the CE itself is domain free, whereas the storage systems (VS and PH) are domain specific (Baddeley, 2000; Engle et al., 1999).

**Aim 2: Relationships among WM measures.** Prior to examining the relationships between clinical measurements of WM as assessed by WISC-IV WM subtests and the WMI index and an experimental computerize change-detection paradigm, bivariate relationships between WISC-IV measures and a computerized clinical measure were examined. Consistent with study hypotheses, differential relationships between WISC-IV WM subtests and the AWMA-2 tasks were found. Specifically, only the Arithmetic subtest was significantly related to both AWMA-2 VWM and VSWM. Digit Span as a whole, and its individual subcomponents (Forward and Backward) were significantly positively correlated with AWMA-2 VWM, but not AWMA-2 VSWM. Notably, neither the Letter-Number Sequencing subtest nor the WMI as a whole were significantly related to the AWMA-2 tasks. This was unexpected, given that previous studies have found significant relationships between the WISC-IV WM subtests and the AWMA-2. For example, one study found mean scores on WM subtest and index scores were higher for average versus low WM groups as classified by the AWMA, and WMI scores were sufficient to assign correct group membership between low and average WM children across individual WMI and individual subtests (WMI Sensitivity = 80%, Digit Span Sensitivity = 91%, Letter-Number Sequencing Sensitivity = 63%; McInnes et al., 2003).
One explanation for the discrepancy in findings may be the content of the AWMA tasks. Specifically, the previous McInnes et al., (2003) study utilized the AMWA as whole to evaluate WM capacity, whereas the current study utilized only one VSWM and one VWM subtest. Moreover, the AWMA includes a number of short-term memory tasks as well. Given that the Digit Span subtest of the WMI includes and equally weights both forward and backward digit span, and forward digit span is a better measure of short-term memory than WM, it may be that previous associations between the AWMA and WISC-IV WM were largely accounted for by short-term memory components of each measure. Overall, it is alarming that two clinical measurements of WM capacity, both of which have been validated and standardized, do not appear to be eliciting or effectively measuring the same construct. Moreover, Arithmetic, the only subtest that was significantly related to both AWMA-2 WM tasks is an optional WISC-IV task, and it is not a standard component of the WMI.

Examination of bivariate correlations between the clinical WM measures and the computerized change-detection task revealed only the Arithmetic subtest of the WISC-IV and the VSWM change-detection task were significantly related, and no other relationships approached significance. This result seems to indicate that apart from the Arithmetic subtest, clinical WM subtests are not eliciting the same construct as experimental WM measures. This again highlights the need for WM theory to guide assessment. Specifically, designing tasks that effectively separate WM components (i.e., VS, PH, CE), and delineate the component being measured is paramount.

In contrast to the current hypotheses, bivariate correlations did not allow for replication of Hill et al.’s (2010) study which evaluated variance accounted for by WAIS-IV WMI subtests in the criterion construct of WM as assessed by experimental WM tasks. Moreover,
the only subtest that was significantly related to the VSWM change-detection task was Arithmetic, a subtest Hill et al. (2010) found was unrelated to WM as measured by experimental paradigms in an adult sample. Still, linear regression analysis revealed the Arithmetic subtest accounted for significant variance in the computerized VSWM change-detection task, along with Anxiety. Similarly, Arithmetic was the only significant predictor of VWM or VSWM as measured by the AWMA-2, though when Phonological Awareness was included as a predictor variable, Arithmetic was no longer a significant predictor of VWM, though it remained significant for VSWM. Although neither phonological awareness nor anxiety is considered to measure of WM, both were found to have some relationship to WM scores in the current study. The relationships of these clinical measures and constructs to WM ability has been previously reported (e.g., Alloway et al., 2009b; Eysenck, Derakshan, Santos, & Calvo, 2007) and lends further support to the notion that experimental and clinical WM are not effectively eliciting the same construct. The relationship between phonological awareness and anxiety to WM and ADHD symptoms will be further discussed later in this section.

In regard to the influence of phonological awareness on eliciting WM, it is important to consider the degree to which language and verbal skills are embedded in tasks. For example, the Arithmetic subtest relies on the ability to process the arithmetic problem being verbally presented. Similarly, the AWMA-2 Listening Recall relies on the ability to process the content of the sentence. In contrast, the computerized change-detection task simply displayed letters. Therefore, although the individual must be able to identify letters, receptive and expressive language functioning are less likely to be elicited. It is notable that since both consonants and vowels are utilized in the stimuli for the VSWM change-detection task, it is possible that participants might chunk letters into words, and this ability would be mediated by
basic language skills. This is unlikely, however, due to fast presentation time (100ms) and arrangement of the letters in a concentric circle. Additionally, the paradigm utilized in the present study was similar to those used previously (e.g., Thomason et al., 2007) that also included both vowels and consonants. In fact, since the current presentation time was faster than that previously utilized for VWM (500ms; Thomason et al., 2007), it is less likely that the current study allowed for chunking or memory strategies than previously published research.

Given that anxiety disrupts the ability to focus attention properly and is more likely to be more disruptive when the stimuli are perceived to be threat-related, or when task stimuli are nonsalient or inconspicuous (Eysenck et al., 2007), it is possible that differing task structure between clinical and experimental tasks may account for the influence of anxiety on performance. Additional research is necessary to further examine this explanation, however, as anxiety was only significantly related to the VSWM change-detection task, and this relationship was positive (indicating either increased anxiety was related to VSWM performance or decreased anxiety was related to lower VSWM). Future studies could test this explanation by systematically manipulating stimuli across paradigms or measuring or manipulating situational stress.

Additionally, unlike the results of Hill et al. (2010) in an adult sample, neither the Matrix Reasoning nor the Vocabulary subtest of the WISC-IV accounted for significant variance in any computerized WM measure beyond that of the Arithmetic subtest. Divergent results between the current study and Hill et al. (2010) could be a result of developmental differences between populations. However, given that research consistently shows that the structure of WM found in adult populations is present as early as age six (e.g, Gathercole et
al., 2004), this explanation is unlikely. Alternatively, discrepant findings might be accounted for by differences in computerized tasks utilized between studies. Specifically, Hill et al. (2010) utilized an automated operation span and an automated listening span task, as well as a modified lag task to evaluate WM capacity experimentally. As these tasks utilize strategies to elicit WM that are somewhat different from computerized change-detection tasks, as well as more similar to strategies used by within Backward Digit Span and Letter-Number Sequencing, it is not surprising that results between studies differ. Moreover, this explanation continues to highlight the importance of careful consideration of WM tasks.

**Aim 3: Relationships between WM and ADHD symptoms.** Given that the WM measures utilized were not significantly consistently intercorrelated, relationships between each measure and ADHD symptoms were examined individually.

**WISC-IV.** In regard to the relationship between WISC-IV measures of WM and ADHD symptoms, bivariate correlations revealed only the Inattention subscales were consistently related to WM performance. The Hyperactive/Impulsive symptoms alone were not significantly related to any of the WMI measures. Moreover, it was notable that the Letter-Number Sequencing subtest was not significantly related to any ADHD symptoms, despite being the measure with the most face validity for eliciting the WM construct (Hill et al., 2010). Within the Digit Span subtest, it appeared that the Digit Span Backward component was likely driving the relationship. This result makes sense, as Forward Digit Span is considered a measure of short-term memory (Jarrold & Towse, 2006), whereas the Backward Digit Span task is more consistent with theories of WM (Beblo et al., 2004).

Although a number of studies question the validity of the Arithmetic subtest due to potentially confounding factors contributing to accuracy on the task (e.g., mathematical effi-
ciency; Stearns, Dunham, McIntosh, & Dean, 2004; & math anxiety; Ashcroft & Kirk, 2001), others have reported mathematical tasks show group differences between ADHD and control groups, as well as ADHD subtypes (e.g., Diamond et al., 2005). The results of the current study are more consistent with the latter results—it was the only measure significantly correlated with both Inattentive and Hyperactive/Impulsive symptoms, although it is not a part of the WMI.

Further examination using regression analyses to examine relationships between ADHD symptoms and WISC-IV WM subtests and the WM index revealed that the ADHD Inattention subscale accounts for significant variance in the WMI as a whole, as well as in the Arithmetic subtest. Moreover, additional linear regression analyses showed both the CTOPP-2 Phonological Awareness Composite and ADHD Inattention subscale account for unique variance in the WMI and Arithmetic subtest. One explanation for this relationship may be due to the task structure of the CTOPP-2 Phonological Awareness Composite. Specifically, each of the three subtests has varying WM demands. In particular, the Elision subtest requires the individual to remove specific phonological segments from spoken words to form new words, which could be a task with high WM load (e.g., holding the word in memory and manipulating it to form a new word). The Phoneme Isolation subtest also contains notable WM demands, in that this task requires the individual to hold a word in memory and isolate a phoneme at a particular location within the word. Therefore, the WM demands inherent in the task structure of Phonological Awareness Composite subtests could account for the relationship between the composite as a whole and WM tasks. As an alternative explanation, this finding is also notable given the significant comorbidity between Specific Learning Disorder in Reading and ADHD (APA, 2014), learning difficulties and WM per-
formance (e.g., Gathercole et al., 2006; Alloway, Gathercole, Kirkwood, & Elliot, 2009c), as well as previous research that reports unique WM profiles for developmental disorders in general (Alloway et al., 2009b). Specifically, consistent with Alloway et al. (2009c), our results suggest children with WM problems are likely to have both poor academic progress in reading and a distinctive profile of inattentive symptoms. Moreover, although these difficulties contribute to and likely exacerbate one another, they also appear to be unique problems in and of themselves. Additionally, it is important to note that although Inattention significantly predicted WM ability when measured continuously, it was not a significant predictor of WM functioning when measured categorically. This finding highlights the importance of considering the diagnosis of ADHD dimensionally, rather than categorically (Lahey, Pelham, Loney, Lee, & Willcutt, 2005) in order to enhance understanding, diagnostic accuracy, and treatment of neurodevelopmental disorders such as ADHD.

**AWMA-2.** On the AWMA-2, although Hyperactive/Impulsive symptoms were not significantly related to performance on this measure, one of the Inattention subscales was significantly related to the VSWM Index. Notably, the VWM Index of the AWMA-2 was not significantly related to any ADHD symptom domains. Although these findings are consistent with some research indicating children with ADHD have fewest deficits in the PH or VWM (e.g., Rapport et al., 2008), it contrasts with other research that indicates children with ADHD have more difficulty with auditory than visual memory items (de Freitas Messina et al., 2006). Additionally, given that the WISC-IV WMI subtests are thought to measure verbal rather than visual WM, and there were significant relationships between the VWM component of the AWMA-2 and WISC-IV WMI subscales, it is somewhat surprising that a similar pattern of relationships between ADHD symptoms and the VWM component of the AWMA-
was not found. However, these results may be accounted for by differences in task demand and structure between tasks. For example, stimuli differences between measures could have accounted for differences. Whereas the WISC-IV WMI subscales primarily use numbers (e.g., Digit Span, Arithmetic) and sequencing (e.g., Digit Span Backward and Letter-Number Sequencing) as stimuli, the AWMA-2 VWM task utilized is more related to literacy than mathematics. Moreover, these results highlight the importance of utilizing both VSWM and VWM tasks in order to better understand the relationship between the WM construct and clinical symptoms such as inattention, hyperactivity, and impulsivity.

**Change-detection tasks.** The computerized change-detection task did not demonstrate significant correlations with any ADHD symptom subscales, though the relationships between the VSWM task performance and the Inattention subscale and ADHD combined symptom count approached significance. Given that the mean WM capacity as measured by the change-detection task indicated it may not be a useful WM measure in children, it is not surprising that relationships between this measure and clinical ADHD scales were not significant.

Overall, although the strengths of relationships varied, it is notable that across WM measures, Inattentive symptoms appear to be more related to WM functioning. These results are consistent with de Freitas Messina et al. (2006), who found that children diagnosed with ADHD-I demonstrate more WM difficulties that other subtypes, as well as Alloway et al. (2009c), who note children with WM problems have a highly distinctive profile of inattentive behavior. Moreover, these results seem to indicate that WM may be a useful construct to consider when evaluating ADHD-I symptoms, though not as useful for ADHD-HI or ADHD-
C, and may even suggest that ADHD-I would best be considered a disorder distinct from ADHD-C, as suggested by Milich, Balentine, & Lynam (2001).

**Aim 4: WM and ADHD classification.** In order to further evaluate the utility of utilizing WM functioning to classify ADHD, analyses were conducted to evaluate ADHD classification dimensionally via continuous symptoms, as well as categorically.

*Continuous ADHD symptoms.* As only Inattentive subscales were significantly related to WISC-IV WM assessment, analyses were only able to examine ADHD-I. Stepwise multiple linear regressions revealed that the WMI as a whole consistently accounted for less variance in Inattentive symptoms than individual subtests. Specifically, Arithmetic alone accounted for significant variance in the Inattentive subscale. Digit Backward alone accounted for significant variance in the ADHD Inattention subscale; Arithmetic did not account for unique variance in this subscale. In order to understand differential results between the Inattentive and ADHD Inattention subscale, consideration of the content of the scales is important. Specifically, the Inattention scale was designed to assess the general content area of inattention, and it includes items that assess both the general concept of inattention and items that describe problems associated with inattention (including some DSM ADHD Inattention items). In contrast to other scales on the Conners 3, which were developed via factor analysis, this scale was developed rationally; that is, items were included based on theoretical and clinical significance, as determined by both clinical experience of the author and scientific literature (Conners, 2009). The DSM ADHD Inattention subscale is made up of items containing symptom level information from the DSM. Therefore, the current results seem to indicate that when considering the relationship between WM constructs and ADHD symptoms, whereas the Arithmetic subscale is most related to inattention symptoms in general, the Digit
Span Backward subscale is more related to clinical measurement of ADHD symptoms and DSM-based diagnostic criteria. See Appendix E for a comparison of items from the Inattention, ADHD Inattention scale, and DSM-IV diagnostic criteria.

Overall, it is important to note that although WM subtests were able to account for significant variance in ADHD subscales, the majority of variance across analyses remained unexplained. There are two primary explanations for these results. It is possible that the WM construct is not being adequately elicited by the WISC-IV subtests, and therefore the methodology utilized within this study does not have sufficient strength or statistical power to measure these relationships effectively with the current sample size. This explanation is supported by the lack of VSWM measurement included in WISC-IV subtests, reliance primarily on span tasks for WM measurement, despite a body of research suggesting these are not the most appropriate measure of WM (e.g., Cowan, 2000), and controversy surrounding use of the Arithmetic subtest (Shelton, Elliott, Hill, Calamia, & Gouvier, 2009)—the subtest most consistently related to other WM measurement modalities (e.g., computerize change-detection tasks, AWMA-2). Alternatively, these results could indicate that WM is not the core deficit underlying ADHD symptoms, as suggested by Rapport et al. (2001). Rather, although WM capacity is associated with ADHD symptoms, it cannot fully explain the disorder. Instead, other theories of ADHD, such as behavioral inhibition models (e.g., Barkley, 1997; Sonuga-Barke, 2002) may better explain the underlying processes resulting in ADHD symptom profiles.

**Categorical ADHD diagnosis.** Despite the significant variance in ADHD symptoms unexplained by WM functioning as measured by the WISC-IV subtests, continuous or dimensional consideration of symptoms still allows for greater understanding of ADHD than
categorical consideration. Specifically, ROC curves revealed that neither utilizing cut-points based on DSM-5 symptom count from the Conners-3P, nor history of diagnosis of ADHD resulted in acceptable specificity or sensitivity as assessed by either the WISC-IV WM sub-tests or the computerized change-detection tasks. It is important to note, however, that as both community and clinical populations were recruited, only 20% of the sample was previously diagnosed with ADHD. Therefore, these analyses were underpowered. Overall, these results seem to indicate evaluating ADHD continuously rather than categorically allows for greater understanding of both the clinical presentation of ADHD and the relationships between ADHD symptoms and cognitive functioning.

**Limitations**

One limitation of the current study is due to sample size. Specifically, although the sample size was adequate for the analyses conducted, increased size would have increased power and ability to evaluate for potential covariates. Still, the sample size was similar to previous studies utilizing (Thomason et al., 2007), validating (Luck & Vogel, 1997), as well as examining developmental changes in WM (Bo et al., 2009) with the change-detection paradigm. Additionally, as this study recruited children from 6 to 12 years old, but it did not control for the number of children within each age, it is possible that developmental differences obscured the utility of the computerized change-detection task. Still, this age range is similar to other studies utilizing a similar task in children (Thomason et al., 2007).

Another limitation is the recruitment of both individuals seeking clinical services and from the larger community who were not service-seeking. It is possible that those who are service-seeking have a clinical presentation different from those recruited from the community. As the recruitment source was not recorded, it was not possible to evaluate these potential
group differences. However, this design allowed for measuring the spectrum of ADHD symptoms, which was a main goal of the study and most similar to population prevalence of ADHD symptoms.

An additional concern is that the measurement of ADHD symptoms was restricted to parental report via the Conners-3P. Clinical diagnosis requires symptoms to be present in more two or more settings; therefore, it is possible that evaluation of symptoms in an additional setting, such as via a teacher report, would have allowed for greater understanding of the relationship between WM and ADHD symptoms. As validation of the Conners-3 rating scales indicates that inter-rater reliability between parents and teachers is moderate ($k = .49$), it is considered acceptable, but this also supports the value of eliciting both perspectives.

Another limitation of this study is that the possibility of circular reasoning. For example, which comes first, the ADHD symptoms or WM problems? Do attention problems cause WM difficulties, or do WM deficits cause ADHD symptoms? As mentioned previously, Rapport et al. (2001) posit that deficits in WM lead to ADHD symptoms. However, other theories, suggest that WM capacity is limited by attentional control (e.g., Engle et al. 2004), and that the ability to maintain units in the focus of attention during a hyperactivated state requires controlled, limited-capacity attention— or the CE component of Baddeley and Hitch’s original model of WM (1974). Therefore, as ADHD is a disorder marked by a “persistent pattern of inattention and/or hyperactivity/impulsivity” (APA, 2014; pg. 31), if WM is limited by attentional control it becomes impossible to evaluate which comes first— the WM deficit (caused by inattention) or inattentive symptoms of ADHD, as they are one and the same.

**Future Directions and Implications**
This study demonstrated a number of strengths. First, this was the first study to directly compare performance on the computerized change-detection task between children and adults. By doing this, it is possible to better understand the utility of experimental tasks frequently utilized in adults for assessment in children. Moreover, the present study is one of the first to specifically compare clinical and experimental WM tasks in children. As discussed previously, as clinical understanding of diagnoses is based on experimental research, it is paramount that the same construct is being elicited between experimental and clinical settings. Experimental researchers must begin to consider the feasibility of utilizing experimental paradigms in clinical settings. Clinicians must be aware of the potential differences between experimental and clinical measurements and select and interpret measures with these in mind. By bridging experimental research and clinical practice, diagnosis and treatment could be enhanced.

Another strength of this study is the measurement of symptoms of ADHD rather than diagnosis. Most studies group ADHD by subtypes or presentations, potentially limiting generalization to other subtypes or presentations (Holmes et al., 2010), do not report ADHD subtypes included in samples (e.g., Klinberg et al., 2002), and do not assess for severity of symptom presentation. However, latent class analysis has been utilized in a few ADHD studies (e.g., Elia et al., 2009; Ostrander et al., 2008) and shown potential, though none of these compared ADHD and WM. Therefore, the ability to evaluate relationships based on number of symptoms is unique to this study and enhances understanding of ADHD symptoms and diagnosis with regard to the WM construct.

Although several limitations in the extant literature regarding WM measurement and the relationship between ADHD symptoms and WM were addressed by this study, there are
many remaining questions to be explored. For example, future research should continue to include both clinical and non-clinical groups in order to better understand the continuum of symptoms characteristic of ADHD and other psychological diagnoses. Specifically, matching clinical and non-clinical participants in order to compare group differences would help to further understand relationship between ADHD and WM. Additionally, since this study largely included children who were not diagnosed with ADHD, only three were currently prescribed a stimulant medication, and these were not taking medication at the time of participation. Examining the effect of prolonged stimulant use on WM and ADHD symptoms as well as the effect of medication versus no medication on WM performance within children remain important areas for future research. In addition to medication, the effect of other treatments of ADHD and their effect on WM are promising areas for future research. For example, what effect does behavior therapy (e.g., behavioral parent training and classroom management), the only evidence-based psychosocial treatment for ADHD children (Pelham, 2001), have on WM performance? Additionally, the utility of WM training for ADHD has been receiving a great deal of attention in recent years and has shown some promise for improving WM functioning in children with ADHD (e.g., Holmes et al., 2010), though its effect on other domains of functioning such as nonverbal reasoning, attention, or academic achievement is negligible (Melby-Lervag & Hulme, 2013). Large trials specifically examining children with ADHD of different ages, presentations, comorbidity, and intellect remain an area of future research that could potentially enhance understanding WM and ADHD (Barkley, 2006). Finally, longitudinal research assessing WM and ADHD symptoms, and considering change of diagnosis from ADHD-C to ADHD-I over time is a fruitful area of future research. Specifically, as one of the controversies in ADHD diagnosis concerns the instability of the ADHD profile in in-
dividuals over time (Lahey et al., 2005), evaluating the WM profile in individuals across ages and diagnostic presentations would aid in better understanding the influence of WM on ADHD symptoms.

The results of this study have clinical implications for both assessment and treatment. In terms of assessment, as mentioned previously, it is paramount that clinicians consider potential differences between experimental and clinical measurements and select and interpret measures with these in mind. The results of this study indicate that the WISC-IV WM subtests do not seem to be consistently eliciting the same construct as either other clinical measures of WM (AWMA-2) or experimental measures (computerized change-detection tasks), with the exception of the Arithmetic Index. Notably, the Digit Backward subtest was correlated with clinical VWM, but not VSWM tasks. Although this calls into question the utility of WISC-IV for comprehensive measurement of WM, it is encouraging to note that since this study was conducted, the WISC-V (2015) has been released, with significant changes in subtest composition. Specifically, the Digit Span task was revised and now includes a sequencing condition, and the Letter-Number Sequencing subtest has been replaced by a VSWM task—Picture Span. Therefore, one of the primary criticisms of this measure, lack of VSWM measurement, has been addressed; though confounding problems within the Digit Span task remain, the construct similarity between new measures (e.g., Picture Span) and experimental measures of WM have yet to be explored. Additionally, the Arithmetic subtest has been removed from the measure entirely.

In terms of treatment implications, the results of this study reveal that although there are relationships between WM functioning and ADHD symptoms, significant variance remains unexplained. Therefore, despite the argument put forth by Rapport et al. (2001) that
treating core deficits in ADHD (e.g., WM) rather than peripheral symptoms (e.g., inattention, hyperactivity, impulsivity) would lead to increased treatment gains, results of the current study indicate it is unlikely that targeting WM alone will reduce ADHD symptom presentation. Rather, findings are consistent with Pelham’s (2001) argument that behavioral intervention, including functional analysis and treatment of target behaviors, is the most appropriate, evidence-based psychosocial treatment of ADHD. In addition, neuropsychological assessment to elucidate cognitive strengths and weaknesses at the individual level should also guide treatment, consistent with a multi-trait, multi-method approach to diagnosis and treatment of ADHD.
References


Diamond, A. (2005). Attention-deficit disorder (attention-deficit/hyperactivity disorder without hyperactivity): A neurobiologically and behaviorally distinct disorder from atten-


age/rehearsal capacity on observed inattentive behavior. *Journal of Abnormal Child Psychology, 38*(2), 149-161.


Wilding, J. (2001). Over the top: Are there exceptions to the basic capacity limit?. *Behavioral and Brain Sciences*, 24(01), 152-153.


Appendix A: DSM-IV-TR, DSM-5, and ICD-10 Criteria for ADHD

Criteria for ADHD (common across DSM-IV-TR, 5 and ICD-10; DSM-5 changes in italic)
1. Fails to give close attention to details or makes careless mistakes in schoolwork, work, or other activities
2. Often has difficulty sustaining attention in tasks or play activities
3. Often does not seem to listen when spoken to directly
4. Often does not follow through on instructions and fails to finish schoolwork, chores, or duties in the workplace
5. Often has difficulty organizing tasks and activities (ICD-10: … is often impaired in organizing tasks)
6. Often avoids, dislikes, or is reluctant to engage in tasks that require sustained mental effort
7. Often loses things necessary for tasks or activities
8. Is often easily distracted by extraneous stimuli (ICD-10: … by external stimuli)
9. Is often forgetful in daily activities (ICD-10: … in the course of daily activities)
10. Often fidgets with hands or feet or squirms in seat (ICD-10: … on seat)
11. Often leaves seat in classroom or in other situations in which remaining seated is expected
12. Often runs about or climbs excessively in situations in which it is inappropriate
13. Often has difficulty playing or engaging in leisure activities quietly (ICD-10: … is often un-duly noisy in playing or has difficulty in engaging quietly in leisure activities)
14. Is often "on the go" or often acts as if "driven by a motor" (ICD-10: … exhibits a persistent pattern of excessive motor activity that is not substantially modified by social context of demands)
15. Often talks excessively (ICD-10: … without appropriate response to social constraints)
16. Often blurts out answers before questions have been completed
17. Often has difficulty awaiting turn (ICD-10: … fails to wait in lines or await turns in games or group situations)
18. Often interrupts or intrudes on others

Subtypes/Specifiers:
DSM-IV-TR ADHD-I: At least 6 items from items 1-9, hyperactive-impulsive criterion not met for past 6 months
DSM-IV-TR ADHD-HI: At least 6 items from 10-18, inattentive criterion not met for past 6 months
DSM-IV-TR ADHD-C: At least 6 items from 1-9, plus 6 items from 10-18 present for past 6 months
ICD-10 Hyperkinetic Disorder: At least 6 Items from 1-9, plus 3 items from 10-14, plus 1 item from 16-18
DSM-5: Specify current severity (Mild, Moderate, Severe)

Additional DSM-IV-TR (5) Criteria:
A. Some hyperactive-impulsive or inattentive symptoms causing impairment were present before age 7 (before age 12).
B. Some impairment from the symptoms is present in two or more settings
C. There must be clear evidence of clinically significant impairment in social, academic, or occupational functioning.
D. The symptoms do not occur exclusively during the course of a Pervasive Developmental Dis-
order (PDD; *PDD exclusion removed*), Schizophrenia, or other Psychotic Disorder and are not better accounted for by another mental disorder.

**Additional ICD-10 Criteria:**
A. Does not meet criteria for pervasive developmental disorder (F84), mania (F30), depressive (F32) or anxiety disorder (F41).
B. Onset before the age of seven years.
C. Duration of at least six months.
D. IQ above 50.

*Note:* From APA, 2000; WHO, 1993; Adapted from Nigg & Nicholas, 2008
Appendix B: AAP Recommendations for Diagnosis of ADHD

1. In a child 6 to 12 years old who presents with inattention, hyperactivity, impulsivity, academic underachievement, or behavior problems, primary care clinicians should initiate an evaluation for ADHD;
2. The diagnosis of ADHD requires that a child meet DSM-IV criteria
3. The assessment of ADHD requires evidence directly obtained from parents or caregivers regarding the core symptoms of ADHD in various settings, the age of onset, duration of symptoms, and degree of functional impairment. A. Use of [ADHD specific] scales is a clinical option when evaluating children for ADHD. B. Use of broadband scales is not recommended in the diagnosis of children for ADHD, although they may be useful for other purposes;
4. The assessment of ADHD requires evidence directly obtained from the classroom teacher (or other school professional) regarding the core symptoms of ADHD, duration of symptoms, degree of functional impairment, and associated conditions. A. Use of [ADHD specific] scales is a clinical option when evaluating children for ADHD. B. Use of broadband scales is not recommended in the diagnosis of children for ADHD, although they may be useful for other purposes;
5. Evaluation of the child with ADHD should include assessment for associated (coexisting) conditions; and
6. Other diagnostic tests are not routinely indicated to establish the diagnosis of ADHD but may be used for the assessment of other coexisting conditions.

Note: From AAP, 2000, p. 1158
Appendix C: Recruitment Flier

DO YOU HAVE A CHILD BETWEEN 6-12 YEARS OLD?

We are looking for volunteers to participate in a study to help better understand symptoms of ADHD. This study examines the relationship between impulsivity, hyperactivity, and inattention and working memory. Your child will complete approximately one hour of thinking and attention tasks. Parents will complete approximately 20 minutes of questionnaires about their child.

This study is being conducted at the EMU Psychology Clinic.
You will receive $10 for your child’s participation.

Needed are normal, healthy boys and girls who may or may not have ADHD, as well as children diagnosed with ADHD.

For more information or to participate, please contact:
Alison Colbert, M.A., Doctoral Fellow, EMU Psychology Department at acolber1@emich.edu.
Appendix D: Demographic and Screening Form

**Demographic Information (about your CHILD)**

1. Gender: (Circle) MALE  FEMALE

2. Ethnicity: ____________________________

3. Date of Birth: __________

4. Age: ________________

5. Handedness (right or left): ________________

6. Parents’ level of education (for example: GED, high school diploma, bachelor’s degree, master’s degree, doctoral degree, etc.):
   - Father: ______________________________
   - Mother: ______________________________

**Academic History (of your child):**

7. Participant’s current grade or highest grade completed: ______________________________

8. Has the participant been held back one (or more) year(s) in school? (circle) YES  NO

9. Has the participant obtained special education services in school up to now (for example: special education, speech therapy, occupational therapy, social work, etc.)?

**Medical History**

10. Has any member in your family or your spouse’s family been diagnosed with a psychiatric illness such as Depression, Anxiety, Bipolar Disorder (or Manic Depression), Schizophrenia or other? (circle) YES  NO

   If yes, please explain and specify the individual’s relationship to the participant (for example: mother, father, sister, brother, uncle, aunt, etc.)
11. Has any member in your family or your spouse’s family been diagnosed with a psychiatric illness such as Depression, Anxiety, Bipolar Disorder (or Manic Depression), Schizophrenia or other? (circle) YES NO

If yes, please explain and specify the individual’s relationship to the participant (for example: mother, father, sister, brother, uncle, aunt, etc.)

_____________________________________________________________________

_____________________________________________________________________

12. Has any member in your family or your spouse’s family been diagnosed with a specific learning disorder (e.g. reading, writing, math), Autism Spectrum disorder (e.g. Autism, Asperger’s, Pervasive Developmental Disorder), or Attention Deficit Hyperactivity Disorder (ADHD)?

(circle) YES NO

If yes, please explain and specify the individual’s relationship to the participant (for example: mother, father, sister, brother, uncle, aunt, etc.)

_____________________________________________________________________

_____________________________________________________________________

13. Place a check mark (√) in the box next to any of the following diagnoses the participant has previously received and indicate age of diagnosis: (check all that apply)

- □ Attention Deficit/Hyperactivity Disorder (ADHD): Age of diagnosis? __________
  (Subtype: (circle one) Hyperactive-Impulsive, Inattentive, Combined)
- □ Autism / Asperger’s / Pervasive Developmental Disorder: Age of diagnosis? __
- □ Depression: Age of diagnosis? __________
□ Anxiety: Age of diagnosis?_______
□ Obsessive-Compulsive Disorder: Age of diagnosis?_______
□ Conduct Disorder / Oppositional Defiant Disorder: Age of diagnosis?_______
□ other mental health condition (please specify)
________________________________________
14. Is the participant currently prescribed medication? (circle) YES NO
If yes, please name the medications and for what they are prescribed:
Medication | Condition
-------------|----------


15. Please note in the following section any relevant medical or background information not previously mentioned (surgery, hospital stays, imaging scans, etc.).

________________________________________________________
________________________________________________________
________________________________________________________
________________________________________________________
Appendix E: Conners 3-P Inattention, DSM-IV Inattention, and DSM-IV Diagnostic Criteria

<table>
<thead>
<tr>
<th>Conners 3P Questions</th>
<th>Inattention Subscale</th>
<th>DSM-IV Inattention</th>
<th>DSM-IV Diagnostic Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>2. Is forgetful in daily activities.</td>
<td></td>
<td>X</td>
<td>A1i. Is often forgetful in daily activities.</td>
</tr>
<tr>
<td>12. Has trouble staying focused on one thing at a time.</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>23. Has a short attention span.</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>28. Avoids or dislikes things that take a lot of effort and are not fun.</td>
<td></td>
<td>X</td>
<td>A1f. Often avoids dislikes, or is reluctant to engage in tasks that require sustained mental effort (such as schoolwork or homework).</td>
</tr>
<tr>
<td>35. Does not seem to listen to what is being said to him/her.</td>
<td></td>
<td>X</td>
<td>A1c. Often does not seem to listen when spoken to directly.</td>
</tr>
<tr>
<td>44. Has trouble concentrating.</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>47. Doesn’t pay attention to details; makes careless mistakes.</td>
<td></td>
<td>X</td>
<td>A1a. Often fails to give close attention to details or makes careless mistakes in schoolwork, work, or other activities.</td>
</tr>
<tr>
<td>49. Has trouble changing from one activity to another.</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>67. Inattentive, easily distracted.</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>68. Does not follow through on instructions (even when he/she understands and is trying to cooperate).</td>
<td></td>
<td>X</td>
<td>A1d. Often does not follow through on instructions and failed to finish schoolwork, chores, or duties in the workplace (not due to oppositional behavior or failure to understand instructions).</td>
</tr>
<tr>
<td>77. Gets bored.</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>79. Fails to complete schoolwork, chores, or tasks (even when he/she understands and is trying to cooperate).</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>84. Has trouble organizing tasks or activities.</td>
<td></td>
<td>X</td>
<td>A1e. Often has difficulty organizing tasks and activities.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td><strong>88. Gives up easily on difficult tasks.</strong></td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>95. Has trouble keeping his/her mind on work or play for long.</strong></td>
<td>X</td>
<td>X</td>
<td>A1b. Often has difficulty sustaining attention in tasks or play activities.</td>
</tr>
<tr>
<td><strong>97. Loses things (e.g., schoolwork, pencils, books, tools, or toys).</strong></td>
<td></td>
<td>X</td>
<td>A1g. Often loses things necessary for tasks or activities (e.g., toys, school assignments, pencils, books, or tools).</td>
</tr>
<tr>
<td><strong>101. Is easily distracted by sights or sounds.</strong></td>
<td></td>
<td>X</td>
<td>A1h. Is often easily distracted by extraneous stimuli.</td>
</tr>
</tbody>
</table>