IMPACT OF WORKING MEMORY DEFICITS ON ACADEMIC ACHIEVEMENT IN ADOLESCENTS WITH ATTENTION-DEFICIT/HYPERACTIVITY DISORDER

by

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Abstract

This study examined the impact of working memory deficits (WMD) on the academic achievement of adolescents with ADHD. Adolescents (n=79) aged 13 to 17 years with a clinical diagnosis of ADHD were subtyped into those with and without WMD based on impairment in at least two measures, and then compared on their academic achievement and clinical profile. Results indicated that adolescents with ADHD plus WMD (23%) manifest significantly lower academic achievement than those with adequate WM. By contrast, there were no group differences in psychiatric comorbidity, severity of ADHD symptoms and psychological adjustment. We also found a unique contribution of WM to academic achievement over and above that of other clinical features. These findings suggest that WMD compromise the educational attainment of a subgroup of individuals with ADHD. Individuals with ADHD should be screened for WMD to prevent academic failure and WM should be considered as a treatment target.
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List of Abbreviations

**ADHD** = Attention-Deficit/ Hyperactivity Disorder

**ADHD + WMD** = Adolescents with Attention Deficit/Hyperactivity Disorder with Working Memory Deficits

**ANOVA** = Analyses of Variance

**DSM-IV** = Diagnostic and Statistical Manual of Mental Disorders, Fourth Edition

**EF** = Executive Functions

**EFD** = Executive Function Deficits

**K-SADS-PL** = Schedule for Affective Disorders and Schizophrenia for School- Age Children – Present and Lifetime Version

**MANOVA** = Multivariate Analysis of Variance

**SDQ** = Strengths and Difficulties Questionnaire

**SWAN** = Strengths and Weaknesses of ADHD-symptoms and Normal-behaviour scale

**WAIS-III** = Wechsler Adult Intelligence Scale - Third Edition


**WISC-IV** = Wechsler Intelligence Scale for Children - Fourth Edition

**WJ-III** = Woodcock-Johnson-III Test of Achievement

**WM** = Working Memory

**WMD** = Working Memory Deficits

**WRAML-II** = Wide Range Assessment of Memory and Learning - Second Edition
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CHAPTER ONE:

General Introduction and Rationale of Thesis Research
1.1 Overview

The goal of this study was to examine the impact of working memory deficits (WMD) on academic achievement in adolescents with attention-deficit/hyperactivity disorder (ADHD). Academic problems are one of the most prominent and chronic functional impairments associated with ADHD. Although this relationship has been well-documented, far less research has focused on investigating the factors that may explain this association. The cognitive domain of executive function (EF), a collection of higher-order cognitive processes, has been proposed as a contributing factor. However, it is still unclear which aspect of EF accounts for most of the variance in the academic functioning of individuals with ADHD. Consequently, this study focuses on working memory, a central executive function process, known to be related to both ADHD and academic achievement.

1.1.1 Organization of Thesis

This thesis is comprised of three chapters, which are organized around a manuscript. As a result of the manuscript structure of this thesis, there is some overlap between the general introduction (Chapter 1) and conclusions sections (Chapter 3), and the introduction and discussion in the manuscript (Chapter 2). This chapter, Chapter 1, presents a general introduction that includes a review of the background literature and relevant issues, in order to provide a rationale for the objectives of this thesis project. Chapter 2, the central chapter of this thesis, presents the empirical study in a manuscript format. This chapter addresses the central question of whether WMD is one of the factors compromising the academic achievement of adolescents with ADHD. Chapter 3
presents a summary of findings, and highlights the clinical implications of the research contained in this thesis. It also includes a brief review of interventions that target working memory processes relevant to the academic achievement of individuals with ADHD. Finally, Appendix A presents a distinct way of analyzing the data that is not included in the manuscript. In this appendix, the academic achievement of the overall sample of adolescents with ADHD is examined and discussed.

1.2 Attention-Deficit/Hyperactivity Disorder (ADHD)

1.2.1 Definition and Clinical Characteristics

Attention-Deficit/Hyperactivity Disorder (ADHD) is a neurodevelopment disorder characterized by persistent patterns of developmentally inappropriate symptoms of inattention, impulsivity and/or overactivity (American Psychiatric Association, 1994). This disorder is one of the most common mental health disorders of childhood onset, with worldwide prevalence rates estimated at 4-10% (as reviewed by Skounti, Philalithis & Galanakis, 2007). The main diagnostic characteristics for ADHD are laid out in the Diagnostic and Statistical Manual of Mental Disorders, Fourth Edition (DSM-IV-TR; American Psychiatric Association, 2000). According to the DSM-IV, in order to meet criteria for ADHD, an individual must demonstrate six or more out of nine symptoms of inattention or hyperactivity/impulsivity that have persisted for at least six months. In addition, these symptoms must have been evident before the age of seven and must cause clear impairment in functioning in two or more settings (e.g., home and school).
Both community and clinical studies suggest that boys are more likely to be diagnosed with ADHD than girls (Barkley, 2003; Skounti, Philalithis & Galanakis, 2007). Evidence also indicates that individuals with ADHD exhibit high levels of comorbidity with other psychiatric and/or learning disorders, particularly with Oppositional Defiant Disorder, Conduct Disorder, Mood Disorders, Anxiety Disorders and Learning Disabilities (Biederman, Newcorn & Sprich, 1991; Spencer, 2006).

Although ADHD is known to arise in childhood, in many cases, this disorder persists well into adolescence and adulthood. Specifically, between 50% and 80% of children with ADHD continue to meet criteria for the disorder in adolescence (Bagwell, Molina, Pelham & Hoza, 2001; Barkley, 2003), and between 40% and 60% either have significant symptoms or meet criteria for ADHD in adulthood (Barkley, Fischer, Smallish & Fletcher, 2002; Mannuzza et al., 1993, 1998; Weiss & Hechtman, 1993). As a result, individuals with ADHD demonstrate significant, lifelong impairment in cognitive, academic, social and occupational functioning (Biederman et al., 2006a; Mannuzza et al., 1993), with evidence suggesting that ADHD has its greatest functional impact on educational attainment (Barkley, 2002).

1.2.2 ADHD and Poor Academic Outcomes

There is a wealth of evidence documenting an association between ADHD and poor academic outcomes (see Loe & Feldman, 2007 for a review). It has been shown that individuals with ADHD encounter academic difficulties early in life, and that these challenges persist well into adolescence and adulthood. For instance, studies indicate that preschool children with ADHD or ADHD symptoms are more likely to be behind in
basic academic readiness skills (Mariani & Barkley, 1997; DuPaul, McGoey, Eckert & VanBrakle, 2001). In school-age children, symptoms of ADHD have been shown to increase the probability of future grade repetition and the need for special education, and to reduce future reading and math test scores independent of a diagnosed learning disability (Currie & Stabile, 2006). By adolescence and early adulthood, individuals with ADHD have been found to achieve lower grades, to fail more of their courses, to be more often retained in grade or placed in special education, and to have dropped out of school at a higher frequency than typically developing individuals (Barkley, Anastopoulos, Guevremont, & Fletcher, 1991; Barkley, Fischer, Smallish & Fletcher, 2006; Biederman et al, 2006a; Fletcher & Wolfe, 2008; Mannuzza et al., 1993, 1998; Weiss & Hechtman, 1993). Moreover, few people with ADHD enter college, and of those who do, only 5% actually graduate (Barkley, 2002). However, some studies suggest that there is variability in terms of academic outcomes and that not all individuals with ADHD manifest academic problems (Frazier et al., 2007; Frick et al., 1991; Frick & Lahey, 1991). Overall, the effects of ADHD on educational outcomes are large and are not attributable to comorbid learning disabilities (Currie & Stabile, 2006; Fletcher & Wolfe, 2008) or conduct disorders (DuPaul et al., 2004; Frick et al., 1991; Hinshaw, 1992; Rapport, Scanlan & Denney, 1999).

Given the impact of ADHD on educational attainment, the disorder is associated with substantial socioeconomic costs to individuals, families and society as a whole. For instance, Pelham and colleagues (2007) have documented that ADHD is associated with a substantial incremental cost of education, due to a large proportion of children and adolescents with ADHD receiving special education services and serious disciplinary
infractions. Furthermore, research has shown that ADHD in adulthood is associated with lower occupational attainment and reduced productivity, as well as with substantial financial losses in the workplace (Biederman et al., 2006a; Kessler, Lane, Stang & Van Brunt, 2009; Kessler et al., 2005; Mannuzza et al., 1993). It is estimated that $19.5 billion (US) is lost in human capital per year due to ADHD (Kessler et al., 2005).

In sum, the relationship between ADHD and poor academic functioning is well-documented. Thus, identifying factors that may explain this association is critical in order to develop effective interventions that will help reduce such poor outcomes. One factor that appears to contribute to the educational problems of individuals with ADHD is the cognitive domain of executive function.

1.3 Executive Functions

1.3.1 Executive Functions and ADHD

Executive Functions refer to a collection of higher-order cognitive processes that underlie self-regulation and purposeful, goal-directed behavior (Barkley, 1997; Pennington & Ozonoff, 1996). Executive functions include response inhibition, set shifting, planning, organization and working memory (WM; Doyle, 2006). Impairments in EF have been related to ADHD in theoretical models of the disorder. Specifically, the executive dysfunction theory proposes that the behavioural symptoms of ADHD arise from a primary deficit in a specific EF domain, such as response inhibition or working memory, or from a more general deficit in executive control (Barkley 1997; Castellanos
Support for this theory has been provided by structural and functional neuroimaging studies implicating fronto-striatal and cerebellar brain regions in ADHD, brain areas thought to underlie EF processes (see Durston, 2003 for a review). As well, a large body of neuropsychological research has documented that individuals with ADHD exhibit impairment in a wide range of executive functions across the lifespan (Boonstra, Oosterlaan, Sergeant & Buitelaar, 2005; Doyle, 2006; Hervey, Epstein & Curry, 2004; Nigg, Willcutt, Doyle & Sonuga-Barke, 2005; Seidman, 2006; Willcutt, Doyle, Nigg, Faraone & Pennington, 2005).

1.3.2 Executive Functions in ADHD and Academic Outcomes

Despite the strong associations between ADHD and EF weaknesses, recent evidence indicates that not all individuals with the disorder exhibit EF deficits (Nigg et al., 2005; Seidman, 2006; Willcutt et al., 2005). Thus, in recent years, studies have emerged which explore ADHD heterogeneity from a neuropsychological perspective by subtyping individuals with ADHD based on the presence of EF deficits (EFD; Biederman et al., 2004, 2006b; Loo, et al., 2007; Nigg et al., 2005). These studies have demonstrated that a greater proportion of individuals with ADHD have EFD (30-52%) compared to typically developing controls (12-18%), and that those individuals with ADHD and concurrent EFD exhibit the greatest functional impairment, particularly in academic outcomes. For example, in a study by Biederman et al. (2004), children and adolescents aged 6 to 17 years with and without ADHD were subtyped into those with and without EFD. To create a definition of EFD, several psychometric measures of EF were used, and a cut-off score indicating impairment was created for each measure based
on performance by the control sample: -1.5 SD below the mean of the controls sample for normally distributed variables and the poorest 7th percentile for non-normally distributed variables. Then, these cut-off scores were applied to the ADHD group and EFD was defined as impairment in two or more EF measures. Findings from this study revealed that the ADHD group had a higher frequency of EFD compared to control youngsters. Moreover, those children and adolescents with ADHD and concurrent EFD exhibited greater impairment in academic outcomes, including lower academic achievement and greater rates of grade retention, placement in special education and tutoring, than those with ADHD who had adequate EF and also compared to control youngsters with EFD but no ADHD. These results seemed to indicate that the combination of ADHD symptoms and EFD place this subgroup of individuals with ADHD at greater risk for academic difficulties.

In addition to the study presented above, other studies have found similar results. For example, Loo et al. (2007) found that EFD were significantly more likely to occur in adolescents with ADHD than in a control and a behaviour disorders sample of adolescents, and that those adolescents with ADHD and EFD exhibited worse performance on measures of intelligence, reading fluency and fine motor functioning compared to adolescents with ADHD but adequate EF. An adult study also showed that individuals with ADHD had higher rates of EFD than a control sample of adults; among adults with ADHD, those with concurrent EFD demonstrated lower educational attainment and lower occupational and socioeconomic status than individuals with ADHD without EFD (Biederman et al., 2006b). Moreover, recent evidence suggests that it may not be ADHD per se nor the hyperactivity/impulsivity dimension of ADHD that is
associated with EFD, but rather the inattention symptom dimension (Biederman et al., 2004; Chhabildas, Pennington & Willcutt, 2001; Diamantopoulou, Rydell, Thorell & Bohlin, 2007; Nigg, Blaskey, Huang-Pollock & Rappley, 2002; Nigg et al., 2005; Thorell, 2007; Willcutt et al., 2005).

Collectively, the preceding studies have advanced understanding of factors that contribute to the poor academic outcomes of individuals with ADHD. However, several issues require clarification in order to develop effective interventions. Executive function is an umbrella term for a complex web of cognitive abilities and previous studies have broadly defined EF to include multiple neurocognitive processes assessed by extensive neuropsychological batteries (e.g., Biederman et al., 2004; 2006b). Thus, it is unclear which aspect of EF is most predictive of poor academic outcomes. This thesis investigates the effects of one core EF process—working memory—as described more fully in the following sections.

1.4 Working Memory

1.4.1 Definition and Components

Working memory is considered to be a central component of executive function (Barkley, 2003; Engle et al., 1999; Roberts & Pennington, 1996). Working memory is the ability to temporarily hold and manipulate task-relevant information in mind in order to guide future actions. It is thought to underlie a wide range of complex cognitive abilities such as reasoning, problem-solving, decision-making and comprehension.
Working memory (WM) allows people to understand their immediate environment, to retain information about their immediate past experience, to solve problems and to formulate, relate and act upon current goals (Baddeley & Logie, 1999). Although several theoretical models of WM exist (see Miyake & Shah, 1999 for a review), the most influential model of working memory is Baddeley and Hitch (1974)’s Multi-Component Theory. This theory supports a three-component structure in which the central executive interacts with two subsystems: the phonological loop and the visuospatial sketchpad (Baddeley, 1986; 1996). Whereas the phonological loop (analogous to verbal working memory) is responsible for the temporary storage of auditory-verbal information, the visuo-spatial sketchpad (analogous to visual-spatial working memory) is responsible for the temporary storage and processing of visual-spatial information. The central executive component serves to monitor, revise and manipulate the information in active storage, as well as to act on and integrate information retrieved from long-term memory in order to support complex cognitive activities. This WM model has been extensively studied and has received considerable support (see Baddeley, 1996 for a review).

### 1.4.2 Measuring Working Memory

There is a great variety of approaches to measuring WM ranging from simple span tasks to more complex dual tasks. Span tasks were designed from the perspective of the Multi-Component Theory of WM (Baddeley, 1986) and have well-established validity and reliability (Conway et al., 2005; Waters & Caplan, 2003). Thus, they are often used in empirical studies on WM and are the primary WM measures selected in this
thesis. Span tasks rely on the presentation of either auditory-verbal items (e.g., digits or letters) or visual-spatial locations (e.g., boxes randomly placed in a platform or holes in a two-dimensional plastic sheet) at a relatively rapid rate. The presentation of these items must then be reported immediately after all items have been presented, either in the same (i.e., forward) or reverse (i.e. backwards) order. The processing requirement of span tasks are thought to differ based on the order of recall demanded. That is, forward tasks are believed to activate storage subsystems, while backwards tasks are believed to activate both storage subsystems and the central executive. Span tasks that differ in stimulus modality are also believed to activate separate components of WM (i.e., auditory-verbal or visual-spatial). All of these components of WM have been shown to be interrelated, as demonstrated by auditory-verbal span tasks loading on the same factor as span tasks which required visual-spatial storage and processing (Kane et al., 2004; Lui & Tannock, 2007). In this thesis, we used WM span tasks assessing both modalities and processing demands, in order to comprehensively assess WM and to create a definition of working memory deficits (WMD).

1.4.3 Working Memory and Academic Achievement

There is considerable evidence linking WM capacity to the ability to learn. Specifically, numerous studies have demonstrated that poor working memory compromises learning in key academic areas including English, mathematics and science (Alloway et al., 2005; Bull & Scerif, 2001; Gathercole, Pickering, Knight & Stegmann, 2004; Jarvis & Gathercole, 2003; Swanson, 1999). For example, a prospective longitudinal study examining the relationship between students’ performance on national
curriculum assessment and WM in a community sample of children and adolescents in primary and secondary grades, found that WM predicted academic achievement in English and mathematics in the younger group, and in math and science—but not in English—for the older group (Gathercole et al., 2004). A similar study showed that children failing to reach expected levels of attainment in English and math performed poorly on WM tasks involving both processing and storage of verbal material (Gathercole & Pickering, 2000). Children with poor WM have also been found to make frequent errors in a range of learning activities, such as remembering and carrying out instructions, keeping track of places in tasks and carrying out mental arithmetic (Gathercole, Lamont & Alloway, 2006). In addition, evidence suggests that the relationship between WM and academic achievement cannot be accounted for by differences in more general intellectual abilities (Cain, Oakhill & Bryant, 2004; Gathercole, Alloway, Willis & Adams, 2006).

1.4.4 Working Memory and ADHD

Impairments in WM have been related to ADHD in both theoretical models of the disorder and in empirical studies. Two separate theoretical accounts of ADHD have contended for an association between ADHD and constrains in WM (Barkley, 1997; Rapport, Chung, Shore & Issacs, 2001). Specifically, Barkley’s (1997) theoretical model suggests that individuals with ADHD exhibit a central deficit in response inhibition, which in turn leads to impairment in WM. In contrast, Rapport and colleagues (2001) argue that ADHD results from a primary deficit in WM, which leads to secondary impairments in other executive functions. Even though these models differ in their
perspective as to whether or not WM is a primary deficit in ADHD, both models suggest that WM impairments are characteristic of the disorder.

Empirical studies have also demonstrated associations between ADHD and WM (Hervey et al., 2004; Martinussen et al., 2005; Willcutt et al., 2005). For instance, in a meta-analysis based on data from 16 studies, Martinussen and colleagues (2005) found that children aged 4 to 18 years with ADHD exhibited moderate to large impairments in WM even after controlling for comorbid learning and language disorders. Furthermore, a recent study demonstrated that a greater proportion of children with ADHD show deficits in all subsystems of WM relative to typically developing children of similar age and intelligence, including deficits in the two independent storage subsystems even after controlling for the central executive (Rapport et al., 2008). Despite the evidence associating WM impairments to ADHD, little is known about the implications of WM weaknesses on the functional outcomes of individuals with the disorder.

1.5 Summary and Rationale for the Present Study

The association between ADHD and poor academic outcomes is well-documented. Research in the field of ADHD has also repeatedly demonstrated greater EFD in individuals with ADHD. Recent evidence, however, suggests that there is significant heterogeneity in terms of neuropsychological functioning and academic outcomes among individuals with the disorder. Specifically, studies have shown that only a subgroup of individuals with ADHD presents with psychometrically defined deficits in EF, and that those individuals with ADHD plus EFD demonstrate the poorest
educational outcomes. These studies have advanced our understanding of factors that contribute to the functional impairment of a subgroup of individuals with ADHD. However, the term “executive function” does not define a unitary cognitive process, but rather, has been used to describe multiple processes. Thus, given the scope of the definition of EF, it is necessary to identify the specific cognitive domains that may underlie the academic difficulties of a subgroup of individuals with ADHD, in order to develop effective and specific prevention and intervention approaches. Hence, this study focuses on working memory, a core component of EF known to be related to both ADHD and academic achievement.

1.5.1 **Objectives and Hypothesis**

The overall purpose of this thesis research was to investigate the impact of working memory deficits (WMD) on the academic achievement of individuals with ADHD. Specifically, the primary objective was to examine whether adolescents with ADHD with and without WMD differ in terms of their academic achievement in reading, mathematics and spelling. Based on the literature reviewed above, it was hypothesized that adolescents with ADHD and concurrent WMD would have lower academic achievement across academic domains, compared to those with ADHD but without WMD, and that this pattern would hold for both male and female adolescents with ADHD.

The second objective of this thesis was to examine whether adolescents with ADHD with and without WMD differ in their clinical profile. The purpose of this objective was to evaluate whether the impact of WMD on academic achievement could...
be accounted for by other clinical features, such as a more severe ADHD group in terms of ADHD symptoms or other psychopathology. Given previous research associating EFD to the inattention symptom dimension, it was predicted that adolescents with ADHD and WMD would demonstrate greater severity of inattention symptoms than adolescents with ADHD with adequate WM. Since there is mixed evidence regarding the relationship between EFD and psychological and social functioning (Clark, Prior, & Kinsella, 2002 vs. Biederman et al., 2004), a clear hypothesis regarding whether adolescents with ADHD with and without WMD would differ in terms of other psychopathology was not outlined.

The final objective of this thesis was to examine the contribution of WM to the academic achievement of adolescents with ADHD over and above that of other clinical features. Although previous studies have documented that WM is associated with academic achievement even after controlling for other cognitive processes and reading ability (Berg et al., 2007; Passolunghi, Marzocchi & Fiorillo, 2005; Swanson & Beebe-Frankenberg, 2004; Swanson 1994), to our knowledge no study to date has examined whether the relationship between WM and academic achievement in adolescents with ADHD still holds even after controlling for other clinical characteristics. Thus, this last objective was of an exploratory nature.
CHAPTER TWO:

Impact of Working Memory Deficits on Academic Achievement in Adolescents with Attention-Deficit/Hyperactivity Disorder (ADHD)
2.1 Abstract

**Background:** The association between attention-deficit/hyperactivity disorder (ADHD) and poor academic functioning is well-documented, but factors explaining this relationship are unclear. The present study examined the impact of working memory deficits (WMD) as a contributing factor. **Methods:** Adolescents (n = 79, aged 13 to 17 years) with a confirmed clinical diagnosis of ADHD were subtyped into those with and without a WMD based on impairment in at least 2 working memory measures, and then compared in terms of their academic achievement and clinical profile. **Results:** Male and female adolescents with ADHD plus a WMD (23% of the sample) manifest significantly lower academic achievement than those with adequate WM. However, there were no group differences in psychiatric comorbidity, severity of ADHD symptoms, or psychological adjustment. Dimensional analyses also supported a unique contribution of working memory to the academic achievement of adolescents with ADHD over and above that of other clinical features. **Conclusions:** These findings suggest that WMD compromise the educational attainment of a subgroup of individuals with ADHD. Individuals with ADHD should be screened for WMD in order to identify a subgroup at greater risk for academic failure, and WM should be considered as a treatment target.

**Keywords:** Attention-deficit/hyperactivity disorder, executive function, working memory, adolescents, academic achievement. **Abbreviations:** ADHD: Attention-deficit/hyperactivity disorder; EFD: executive function deficits; WM: working memory; WMD: working memory deficits.
2.2 Introduction

ADHD is a prevalent, persistent and highly heritable neurodevelopmental disorder of childhood onset that affects about 5% of the population worldwide (Polanczyk, de Lima, Horta, Biederman & Rohde, 2007). This disorder is a major clinical, educational and public health concern because of the associated morbidity and impairment across the lifecycle, as well as resultant socioeconomic costs (Pelham, Foster & Robb, 2007). Academic difficulties are among the most prominent and chronic functional impairments associated with ADHD. For instance, substantial evidence supports a link between ADHD and poor academic outcomes, including low academic achievement, grade retention, special education services and high school drop-out (Barkley, Fischer, Smallish & Fletcher, 2006; Frazier, Youngstrom, Glutting & Watkins, 2007; Loe & Feldman, 2007). These academic challenges and their associated impairment (e.g., underemployment) persist well into adolescence and adulthood (Biederman et al., 2006a) and are not attributable to comorbid learning disabilities (Currie & Stabile, 2006) or conduct disorders (DuPaul et al., 2004; Hinshaw, 1992). The relationship between ADHD and academic problems is well documented. However, far less research has focused on examining the causes for this association. Moreover, not all individuals with ADHD manifest academic difficulties (Frazier et al., 2007): estimates indicate that approximately 30% underachieve academically (Frick et al., 1991; Frick & Lahey, 1991). These findings have motivated researchers to identify factors that place a subset of individuals with ADHD at greater risk for academic failure.

One factor that may account for the academic difficulties of individuals with ADHD is the cognitive domain of executive function. Executive function (EF) has been
broadly defined as a collection of higher-order cognitive processes underlying goal-directed behaviour, and it includes such abilities as planning, set shifting, response inhibition and working memory (Barkley, 1997; Pennington & Ozonoff, 1996). Impairments in executive function are well-documented in individuals with ADHD across the lifespan (Seidman, 2006; Willcutt, Doyle, Nigg, Faraone, & Pennington, 2005). Recent studies have demonstrated that a greater proportion of individuals with ADHD (30-52%) exhibit executive function deficits (EFD) compared to typically developing controls (12-18%), and that those individuals with ADHD and concurrent EFD demonstrate greater impairment in academic functioning (Biederman et al., 2004, 2006; Loo et al., 2007; Nigg et al., 2005). Studies have also documented that it is the inattention symptom dimension rather than ADHD per se, or the hyperactivity-impulsivity dimension, that is associated with EFD (Biederman et al., 2004; Diamantopoulou, Rydell, Thorell & Bohlin, 2007; Nigg et al., 2005; Thorell, 2007).

Collectively, the preceding studies have advanced our understanding of factors that contribute to the functional impairments in individuals with ADHD. However, EF is an umbrella term for a complex web of cognitive abilities, and most of these studies have broadly defined EF (e.g., Biederman et al., 2004; 2006). Thus, it is unclear which aspect of executive functioning is most predictive of poor academic outcomes. Accordingly, this study focuses on working memory, a core executive function process (Roberts & Pennington, 1996), known to be related to both ADHD and academic achievement.

Working memory (WM) is the ability to store and manipulate information in mind for brief periods of time (Baddeley, 2003). It is a limited capacity, multidimensional construct that is thought to underlie complex mental activities such as
problem-solving, decision-making and reasoning (Miyake & Shah, 1999). According to the three-component model of WM proposed by Baddeley and Hitch (1974), WM involves auditory-verbal and visual-spatial storage systems and a central executive processing system that serves to manipulate stored information. WM has been found to predict academic achievement in key academic areas (Jarvis & Gathercole, 2003; Gathercole, Pickering, Knight, & Stegmann, 2004). In addition, WM processes have been implicated in ADHD in theoretical models of the disorder (Barkley, 1997; Rapport, Chung, Shore, & Isaacs, 2001), and recent meta-analyses have demonstrated that individuals with ADHD exhibit greater WM impairments than typically developing individuals, even after controlling for psychiatric comorbidity (e.g., learning disorders) and general intellectual functioning (Hervey, Epstein & Curry, 2004; Martinussen, Hayden, Hogg-Johnson & Tannock, 2005; Willcutt et al., 2005). Despite these findings, little is known about the functional implications of WM deficits (WMD) in individuals with ADHD. Thus, given the critical importance of WM for adequate academic functioning, and considering the poor academic outcomes associated with ADHD, it is important to assess whether the academic impairments related to ADHD are partly accounted for by deficits in WM.

Accordingly, the purpose of this study was to investigate the impact of WMD on the academic achievement of adolescents with ADHD. Specifically, the primary objective was to examine whether adolescents with ADHD with and without WMD differ in their academic achievement in reading, mathematics and spelling. We focused on adolescents with ADHD, because not only they are understudied (Seidman, 2006), but also because the continued presence of academic problems in this developmental period
will place these youngsters at high risk for underemployment and lower status in terms of human capital (Currie & Stabile, 2006; Groot & van den Brink, 2007; Kessler et al., 2005). The second objective of this study was to examine whether adolescents with ADHD with and without WMD differ in other clinical characteristics that may account for the impact of WMD on academic outcomes. Given evidence from previous research that not all youngsters with ADHD have EFD, it was anticipated that 20-40% of adolescents with ADHD would exhibit WMD. In addition, we hypothesized that those adolescents with ADHD plus WMD would demonstrate lower academic achievement across academic areas compared to those with intact WM, and that this pattern would hold for both male and female adolescents with ADHD. We also expected that those adolescents with ADHD and a concurrent WMD would manifest more severe symptoms of inattention than those with intact WM.

2.3 Method

**Participants**

The sample included 79 adolescents, 58 males (73.4%) and 21 females (26.6%), aged 13 to 17 years (M=15.25, SD=1.43) with a confirmed *Diagnostic and Statistical Manual of Mental Disorders* (4th ed. *DSM–IV*; American Psychiatric Association, 1994) diagnosis of ADHD. These participants were selected from a larger sample of adolescents aged 13 to 18 (n= 170) who had been referred to an outpatient clinic in a metropolitan paediatric hospital for evaluation because of concerns about attention,
behaviour and learning. Prior to the diagnostic assessment, parents and teachers completed ratings scales addressing the adolescents’ ADHD symptoms and psychological adjustment. All adolescents completed a comprehensive diagnostic assessment, which used *DSM-IV* criteria to evaluate the presence of ADHD and comorbid conditions. Exclusionary criteria included a Full Scale IQ score of less than 75 or any evidence of psychosis, a pervasive developmental disorder or uncorrected sensory impairment. All participants had English as their native language.

Of those adolescents who completed the diagnostic assessment, four met the exclusionary criteria, 32 did not meet not criteria for ADHD, 40 were subthreshold and 94 met DSM-IV criteria for ADHD. Adolescents with a confirmed DSM-IV diagnosis of ADHD were selected for the present study based on the following criteria: 1) were between the ages of 13 to 17 years old; 2) had data available on at least three out of the four measures of WM selected for the present study; and 3) had complete data on a standardized achievement test. Adolescents with ADHD not included in this study (n=15) were 18 years old or older and/or did not have complete data available on WM or academic measures.

As expected in a clinic-referred sample, the 79 adolescents included in this study met diagnostic criteria for other comorbid diagnoses: Oppositional Defiant Disorder (20.5%), Conduct Disorder (7.7%), Anxiety Disorder (19.2%), Mood Disorder (2.6%) and Learning Disorder/Learning Disability (32.1%). Also, 37% of this adolescent sample was receiving medication treatment for their ADHD. Medications included immediate-release methylphenidate and various longer-acting formulations of this drug.
Measures and Procedures

Clinical diagnostic interviews

The Schedule for Affective Disorders and Schizophrenia for School-Age Children – Present and Lifetime Version (K-SADS-PL; Kaufman et al., 1997) was used to assess the presence of ADHD and other clinical disorders. The K-SADS-PL is a widely used, well-validated, semi-structured diagnostic interview that provides systematic information from multiple informants about the presence of current and lifetime disorders based on DSM-IV criteria. The K-SADS-PL has adequate test-retest reliability with r=0.63, which is comparable with other psychiatric interviews, and interrater reliability has been reported as 98% agreement (Kaufman et al., 1997). In the current study, interviews were conducted separately with adolescents and parents by a clinical psychologist or a supervised Ph.D. candidate in clinical psychology. All interview items for the ADHD, ODD, CD, Depression and Anxiety disorders were administered (i.e., skip-out rules not used). The final DSM-IV diagnosis of ADHD was based upon the clinician’s summary of information from the parent and adolescent interview and information from teacher reports for evidence of pervasiveness. A Learning Disorder diagnosis was based upon the integration of information from psychometric testing (including evidence of significant processing weaknesses which are significantly lower than would be expected given the adolescent’s overall cognitive abilities), school records and the clinical diagnostic interview and/or a Learning Disorder diagnosis or learning disability identification based on previous reports.
Behavioural Symptoms of ADHD

The *Strengths and Weaknesses of ADHD-symptoms and Normal-behaviour scale* (SWAN; Swanson et al., 2005) was used to assess inattention and hyperactive/impulsive behaviours on a continuum. The SWAN is a rating scale that includes the 18 diagnostic criteria items for ADHD based on the DSM-IV-TR. Each item is rated on a 7-point scale ranging from Far Above Average = -3 to Far Below Average = 3. Hence, this scale better captures a broader range of variation of these behaviours. The SWAN scale was selected for this study because its positively worded items are generally more acceptable to respondents, and its extended scale provides more precise measurement of the two major dimensions of ADHD. The SWAN has adequate cohesiveness among inattention items and hyperactivity/impulsivity items (Lui & Tannock, 2007; Toplak et al., 2009; Young & Hay, 2009). An average score for the Inattention scale and Hyperactivity/Impulsivity scale was calculated for parent and teacher ratings separately. Thus, the higher the averaged score, the more inattentive or hyperactive/impulsive the parent or teacher rated the adolescent.

Psychological Adjustment.

*The Strengths and Difficulties Questionnaire* (SDQ; Goodman, 1997) was used to assess other behavioural, emotional and social difficulties. The SDQ is a brief screening questionnaire of psychological adjustment and broad psychopathology that asks about 25 attributes, some positives and other negatives (Goodman, 2001). Each item is rated on a 3-point Likert scale. Items are divided into the following five scales: emotional symptoms, conduct problems, hyperactivity-inattention, peer relationship problems, and
prosocial behavior (Goodman, 2001). Scores for each scale range from 0 to 10. The SDQ website provides clinical cut-off scores for each subscale (www.sdqinfo.com). This scale has been shown to have adequate internal consistency, reliability and validity (Bourdon, Goodman, Rae, Simpson & Koretz, 2005; Goodman, 2001). The extended version of the SDQ was used in this study, which includes the 25 core items and an impact score. Parent and teacher SDQs were scored separately.

**Academic Achievement**

The *Woodcock-Johnson-III Test of Achievement* (WJ-III; Woodcock, McGrew & Mather, 2001) was used to assess academic achievement in reading, mathematics and spelling. The WJ-III is a widely used, individually administered, standardized test with well-established psychometric properties (Mather & Woodcock, 2001). The *Broad Reading Cluster* provides a comprehensive measure of reading achievement, and it is comprised of the Letter-Word Identification, Reading Fluency and Passage Comprehension subtests. The *Broad Math Cluster* provides a comprehensive measure of math achievement, and it is comprised of the Calculation, Math Fluency, and Applied Problems subtests. The *Spelling* subtest provides a measure of spelling skills. Raw scores were converted to standard scores with a mean of 100 and a standard of deviation (SD) of 15.

**Working memory measures**

Four standardized, clinical measures of working memory span assessing both modalities (i.e., auditory-verbal and visual spatial) and processing demands (i.e., storage
and manipulation of information) were included in this study. Total raw scores for all four tasks were converted to age-adjusted scaled scores with a mean of 10 and a SD of 3 (U.S. norms).

Auditory-Verbal WM was assessed using the Digit Span and the Letter-Number Sequencing subtests both from the Wechsler Intelligence Scale for Children – Fourth Edition (WISC-IV; Wechsler, 2003) for adolescents younger than 17 years of age, and the Wechsler Adult Intelligence Scale-Third Edition (WAIS-III; Wechsler, 1997) for adolescents older than 17. In the Digit Span task, the examiner reads increasingly longer lists of digits at a rate of one digit per second. The participant is asked to repeat the digits in the exact order on the forward trials, and then in the reverse order on the backward trials. In the Letter-Number Sequencing task, the examiner reads a mixed sequence of number and letters at a rate of one item per second. The participant is asked to first repeat the numbers in numerical order, and then the letters in alphabetical order.

Visual-Spatial WM was assessed using the Spatial Span task from the WISC-III-Process Instrument (WISC-III-PI; Kaplan, Fein, Kramer, Delis & Morris, 1999), and the Finger Windows task from the Wide Range Assessment of Memory and Learning (WRAML-II; Adams & Sheslow, 1990). In the Spatial Span task the examiner taps to a sequence of locations on a three-dimensional board upon which cubes are mounted at a rate of one item per second. The participant is asked to replicate the sequence in the exact order on the forward trials, and in the reverse order on the backward trials. In the Finger Windows task, the examiner points to an increasingly longer sequence of holes arranged on a vertically-presented white card with window-like openings. The participant is then asked to reproduce the exact spatial sequence using a finger.
**Procedure**

All adolescents were tested individually by a registered clinical psychologist or by graduate students under supervision. Testing was conducted in a quiet room at the hospital over the course of one day. All measures were administered in a standardized fashion as prescribed by the test manuals. Adolescents with ADHD who were currently being treated with stimulant medication were asked to discontinue medication for at least 24 hours prior to the assessment, and were tested while off their medication.

**A Categorical Definition of Working Memory Deficits (WMD)**

The four measures of WM were used to create a binary impairment indicator of WMD. We used scaled scores to account for age-related maturational changes in WM, and in order to make comparisons to the broader population in which these measures were standardized. A scale score ranging from 8 to 12 (25th to 75th percentile) is considered to be within the average range of functioning. For each of the WM measures, we defined a threshold indicating poor performance as a standard score of 7 or less (i.e., 16th percentile or lower), which is -1 standard deviation below the mean (Binder, Iverson, & Brooks, 2009). We then defined a subject as having WMD, if two or more tests showed impairment. Three issues contributed to this choice of cut-off. Firstly, although our cut-off is broader than previous studies on EFD (e.g., Biederman et al., 2004; 2006b; Loo et al., 2007; Nigg et al., 2005), it seemed appropriate given our use of scale scores and the fact that we were only categorizing WM and not several measures of EF. Secondly, we considered it inappropriate to place individuals with two test scores in
the below average range, in the adequate WM group (Biederman et al., 2004). Thirdly, whereas one low score may be due to chance, two or more scores at the 16th percentile or less would likely be interpreted as an area of vulnerability or difficulty by a clinician (Binder et al., 2009; Holmes, Gathercole & Dunning, 2009). Based on this definition, adolescents with ADHD were dichotomized into two groups: adolescents with ADHD without WMD (ADHD), and adolescents with ADHD with concurrent WMD (ADHD + WMD). Adolescents aged 17 years old (n=10) did not complete the Spatial Span task, as the norms for this test range from 6-16 years of age. These adolescents were considered as demonstrating average performance on the task in question.

To justify our analytical decision to treat the four working memory measures as a unitary construct of WMD, we subjected the scores to factor analysis. We used all of those adolescents aged 13 to 17 (those with and without ADHD and those with subthreshold symptoms) who had data available on the WM measures (n=150) to provide sufficient power for a principal axis factoring, which was performed. The results confirmed the existence of a single factor with Eigen values greater than 1. The Eigen value was 2.265, which accounted for 42.95% of the variance. The factor loadings for individual working memory tasks were Spatial Span (.79), Digit Span (.66), Letter Span (.58) and Finger Windows (.57). When the factor analysis was repeated using only participants with a confirmed diagnosis of ADHD (n=79), results remained unchanged (i.e. a single factor was found). This analysis supports the notion that the four WM task are all measuring a single latent construct, regardless of modality or processing demand.
**Statistical Analysis**

Analyses were conducted using the Statistical Package for the Social Science (SPSS/PC) version 17.0 for Windows. Chi-Square ($X^2$) and t-test analyses were used for group (2: ADHD; ADHD + WMD) and gender (2: Males; Females) comparison on demographic variables, individual WM measures, and comorbidity with other psychiatric disorders as determined by the clinical assessment. Multivariate analyses of variance (MANOVA) with group and gender as between-subjects factors were conducted on variables assessing academic achievement (Reading Cluster, Math Cluster, Spelling subtest), behavioural symptoms of ADHD (parent and teacher SWAN Scales) and psychological adjustment (parent and teacher SDQ scales). Separate MANOVAS were used for parent and teacher ratings and all subscales of each rating scale were entered in one test of MANOVA. When the omnibus test, using Wilks’ Lambda, was statistically significant ($p < .05$), follow-up analyses of variance (ANOVAS) were examined. Partial eta-square ($\eta_p^2$) were calculated as a measure of effect size and interpreted as the following: small > .05, medium > .1, and large > .2 (Cohen, 1969).

As an additional analysis, correlations and hierarchical multiple regression were conducted to take a dimensional approach at examining the impact of WM on academic achievement. Given that the factor analysis revealed only one component with all WM tasks loading on the one extracted factor, a continuous WM composite score was computed for each participant (i.e., the average scale score of all WM tasks). Correlational analysis was performed to examine relationships between the WM composite, academic achievement and ADHD symptoms. Since ADHD medication treatment and a comorbid Learning Disorder may impact academic achievement, these
variables were also included in the analysis. Hierarchical regressions were conducted with Broad Reading, Broad Math and Spelling as the dependent variables. In Step 1 the following predictors were entered simultaneously in the regression equation: inattention symptoms, hyperactivity/impulsivity symptoms, ADHD medication status and comorbid Learning Disorder. The WM composite was entered in Step 2 to examine how much of the variance in academic achievement is accounted by WM performance, over and above that of the predictors entered in Step 1. All statistical tests were two-tailed. The level of significance was set at $\alpha = 0.05$.

2.4 Results

Characteristics of adolescents with ADHD with and without WMD

Means and standard of deviations for demographic characteristics, comorbid conditions and performance on each of the WM measures, stratified by WMD group, are presented in Table 1. Eighteen adolescents with ADHD (23%) were classified as having WMD. As shown in Table 1, there was no statistically significant difference between adolescents with ADHD with adequate WM and adolescents with ADHD with WMD in age, gender, ADHD medication status, and parental educational level ($X^2 (6) = 8.86, p = 1.82$). When gender differences were examined, there was no statistically significant difference on any of the above variables, except for a small but significant difference in age, with females being slightly older ($M = 15.90$, $SD = 1.18$) than males ($M = 15.01$, $SD = 1.44$; $t (77) = -2.51$, $p = .014$). Adjustment was not necessary given that all main
variables were normed-referenced. In addition, there were no statistically significant differences between WMD groups on comorbidity with other psychiatric disorders (all p-values > .05). However, there was a statistically significant difference between males and females in comorbidity with an Anxiety Disorder, with females with ADHD being more likely to have a comorbid anxiety disorder compared to male adolescents with ADHD ($X^2(2) = 11.236, p = .004$). To provide a meaningful illustration of our definition of WMD, we conducted t-tests on each of the four WM measures. As shown in Table 1, there were statistically significant group differences on each WM measure, supporting our construct of WM deficits (all p-values < .001). There were no gender differences on any of the four WM measures (all p-values > .05).

*Academic Achievement in Adolescents with ADHD with and without WMD*

Means, standard of deviations, critical values and effect sizes ($\eta^2_p$) for the effects of WMD group on academic achievement are shown in Table 2. There was a significant main effect for group (ADHD, ADHD + WMD) on academic achievement, of medium effect size (Wilks’ Lambda = .853, $F (3, 73) = 4.199, p = .008, \eta^2_p = .147$). There was no significant main effect for gender (Wilk’s Lambda = .957, $F (3, 73) = 1.100, p = .355, \eta^2_p = .043$); and no Group x Gender interaction on academic achievement (Wilks’ Lambda = .976, $F (3, 73) = .606, p = .613, \eta^2_p = .024$). As shown in Table 2, univariate analyses revealed that there were significant effects of group on Broad Reading, Broad Math and Spelling, with adolescents with ADHD plus WMD scoring significantly lower across academic domains compared to adolescents with ADHD but adequate WM. To further examine the impact of WMD group and gender on specific academic skills, two-way
analyses of variance (ANOVA) were performed on the subtests comprising the Broad Reading and Broad Math Clusters. As displayed in Table 2, there were significant group effects on the Letter-Word Identification, Reading Fluency, Passage Comprehension, Calculation and the Applied Problems subtests (all p-values < .05), with adolescents with ADHD and WMD performing significantly lower than adolescents with ADHD but adequate WM. Although adolescents with ADHD and WMD scored lower on the Math Fluency subtest than adolescents with ADHD but adequate WM, this difference was not statistically significant. There were no significant effects of gender, and no Group x Gender interactions on any of the subtests comprising the Broad Reading and Broad Math clusters (all p-values > .05).

**Behavioural Symptoms of Adolescents with ADHD with and without WMD**

Means and standard of deviations for the SWAN parent and teacher ratings of inattention and hyperactivity/impulsivity symptoms, stratified by WMD group are presented in Table 3. As shown in Table 3, there was no significant main effect for group on the SWAN ADHD symptoms scale as rated by either parents or teachers. Univariate analyses revealed no significant differences between adolescents with ADHD with adequate WM and adolescents with ADHD with WMD on severity of symptoms of inattention and hyperactivity/impulsivity as rated by either parents or teachers (all p-values > .05). In addition, there were no significant main effects for gender on symptoms of ADHD as rated by parents (Wilks’ Lambda = .983, F (2, 72) = .637, p = .532, $\eta^2_p = .017$) or teachers (Wilks’ Lambda = .953, F (2, 70) = 1.738, p = .183, $\eta^2_p = .047$); and no Group x Gender interaction on either the parent (Wilks’ Lambda = .976, F
(2, 72) = .880, p=.419, \( \eta^2_p = .024 \) or teacher (Wilks’ Lambda = .955, F (2, 70) = 1.656, 
p = .198, \( \eta^2_p = .045 \) SWAN symptom rating scales.

*Psychological Adjustment of Adolescents with ADHD with and without WMD*

Means and standard of deviations for the parent and teacher SDQ, stratified by WMD group are presented in Table 3. As shown in Table 3, there were no significant main effects for Group on the parent SDQ or teacher SDQ; and no significant Group x Gender interaction on the parent SDQ (Wilks’ Lambda = .926, F (6, 70) = .927, p = .481, 
\( \eta^2_p = .074 \) or teacher SDQ (Wilks’ Lambda = .975, F (6, 67) = .286, p = .942, \( \eta^2_p = .025 \)). Follow-up univariate analyses on each SDQ scale revealed no significant group differences and no significant interactions for either parent or teacher ratings (all p-values > .05). By contrast, there were significant main effects of gender on the parent SDQ (Wilks’ Lambda = .815, F (6, 70) = 2.654, p = .022, \( \eta^2_p = .185 \) and teacher SDQ (Wilks’ Lambda = .768, F (6, 67) = 3.336, p = .006, \( \eta^2_p = .232 \)). Univariate analyses revealed that parents rated females with ADHD as having greater Emotional Symptoms than males adolescents with ADHD (F (1, 75) = 6.175, p = .015, \( \eta^2_p = .076 \)), and that teachers rated male adolescents with ADHD as having greater Conduct problems (F (1, 72) = 6.154, p = .015 \( \eta^2_p = .079 \)), Hyperactivity- Inattention symptoms (F (1, 72) = 11.279, p = .001 \( \eta^2_p = .135 \) and Peer Problems (F (1, 72) = 7.134, p = .009, \( \eta^2_p = .09 \) and less Prosocial Behaviour (F (1, 72) = 6.568, p = .012 \( \eta^2_p = .084 \) than female adolescents with ADHD.
Intercorrelations between measures are presented in Table 4. There was a significant positive relationship between WM performance and Broad Reading, Broad Math and Spelling. There were no significant relationships between WM performance and hyperactivity/impulsivity symptoms as rated by both parents and teachers, nor between WM performance and inattention symptoms as rated by parents. By contrast, there was a significant negative relationship between teacher ratings of inattention and WM performance. However, there was no relationship between inattentive symptoms and WM performance when controlling for hyperactive symptoms as rated by both parents and teachers (all p-values > .05). Similarly, there was no relationship between hyperactive/impulsive symptoms and the WM composite when controlling for inattentive symptoms as rated by either parents or teachers (all p-values > .05).

Multiple regression results including the R square change ($\Delta R^2$), F change ($\Delta F$), standardized regression coefficients ($\beta$), and t-test for the regression coefficients are presented in Table 5. As shown in Table 5, Step 1 was significant in the three regressions equations, with a Learning Disorder contributing a significant amount of variance across academic domains and teacher ratings of inattention contributing significant variance to Broad Math. Of particular importance, the R square change in Step 2 was significant for Broad Reading ($F(1, 65) = 14.275, p < .001$), Broad Math ($F(1, 65) = 22.145, p < .001$) and Spelling ($F(1, 65) = 6.552, p = .013$), indicating that WM performance contributes a significant amount of unique variance to academic achievement over and above that of inattention and hyperactivity-impulsivity symptoms,
ADHD medication status and comorbid Learning Disorder. Specifically, WM performance contributed 14% of unique variance to Reading, 20% to Math and 7% to Spelling when statistically controlling for the predictors entered in Step 1. When the three hierarchical regressions were repeated by entering the dichotomous definition of WMD in Step 2, the pattern of results was identical to that reported above for the continuous indicator of WM. In addition, regression analyses were repeated by reversing the order of entry between the WM composite (entered in Step 1 along other predictors) and Learning Disorder (entered in Step 2), and both WM performance and Learning Disorder remained statistically significant across the three academic domains. When regressions were repeated entering parent ratings without teacher ratings into the regression equation in Step 1, and then teacher ratings without parent ratings, the pattern of results remained the same. Finally, we repeated regressions by entering symptoms of inattention (parent and teacher ratings) without hyperactivity/impulsivity symptoms into the regression equation in Step 1 along with other predictors, and then hyperactivity/impulsivity symptoms without symptoms of inattention. All betas values across regression equations for inattention symptoms and then hyperactivity/impulsivity symptoms were non-significant (all p-values > .05).

2.5 Discussion

The purpose of the present study was to investigate the impact of working memory deficits on the academic achievement of adolescents with ADHD. To our knowledge, this is the first study to directly subtype individuals with ADHD based on the
presence of WMD, and to compare them in terms of their academic achievement and other clinical characteristics. Major findings from this study were that adolescents with ADHD and a concurrent WMD demonstrated lower academic achievement across academic domains compared to adolescents with ADHD but adequate WM. These effects were evident regardless of gender and could not be accounted for by differences in medication status, comorbidity with other psychiatric disorders, severity of ADHD symptoms or other behavioural, emotional or social difficulties. WM performance was also found to contribute significant and unique variance to academic achievement in reading, mathematics and spelling over and above other clinical features. Taken together, these findings suggest that deficits in WM is one of the factors compromising the academic functioning of a subgroup of individuals with ADHD, and that the impact of WMD on academic achievement is not simply an expression of a subset of other clinical characteristics.

Based on our categorical definition of WMD, deficits in WM were evident among 23% of adolescents with ADHD. This percentage is broadly consistent with previous studies on EFDs in ADHD, which have shown that only a subset of individuals with the disorder exhibit impairment in EF (Biederman et al., 2004, 2006b; Nigg et al., 2005; Loo et al., 2007). Our results further suggest that the cognitive deficits in WM related to ADHD are not present among all individuals with the disorder, and are not an essential and necessary feature of ADHD, as has been previously emphasized (Castellanos, Sonuga-Barke, Milham & Tannock, 2006; Nigg et al., 2005). Thus, deficits in WM should be seen as a discrete cognitive comorbidity that can have significant detrimental effects upon the academic achievement of individuals with ADHD, and not as a
diagnostic indicator. It is important to note, however, that we may be underestimating the true magnitude of WM deficits in the ADHD population. Our definition of WMD was based on clinical, psychometric measures of WM, which are brief in duration and administered under optimal, highly controlled conditions where there are limited distractions. Thus, poor performance on these measures may be capturing deficits in WM in only the most severe cases. Nonetheless, the validity of our definition of WMD (using psychometric test scores) was supported by the lower academic achievement of this subgroup. That is, our definition proved effective in identifying a subgroup of individuals with ADHD who demonstrate significantly lower academic performance. Future work should investigate other operational definitions of WM, as well as further evaluate our proposed definition of WMD and its clinical and research utility.

As hypothesized, the effects of WMD were evident across achievement domains with adolescents with ADHD and WMD scoring significantly lower in reading, mathematics and spelling. WM was also found to contribute significant unique variance across academic domains over and above that of other clinical features. When examining specific academic areas, we found that our binary definition of WMD had the greatest effect at discriminating academic achievement in reading (medium to large effect size), rather than mathematics or spelling. On the other hand, the overall sample of adolescents with ADHD demonstrated lower performance as a group in mathematics than in reading or spelling. This finding is consistent with previous research documenting greater math difficulties in individuals with ADHD than in the general population (Capano, Minden, Chen, Schachar & Ickowicz, 2005; Mayes & Calhoun, 2006). These math difficulties were particularly evident in the Math Fluency subtest, a simple task requiring
participants to solve basic arithmetic calculations within a 3-minute time limit. Both 
groups, regardless of WM performance, scored approximately -1 SD below the mean in 
this task. In contrast, performance on the Applied Problems subtest, a task requiring 
applied math reasoning, was within the average range of performance for both groups. 
This pattern of findings may suggest that the math difficulties of individuals with ADHD 
may be a result of delayed automaticity with math facts and/or weaknesses in procedural 
knowledge, rather than in problems with math reasoning (Mather & Jaffé, 2002). It is 
also possible that the nature of the Math Fluency task (timed, requiring rapid and 
accurate processing of operation signs) may place greater demands on cognitive 
processes known to be compromised in ADHD, such as WM and sustained attention, 
which have also been shown to be critical for optimal math performance (Berg et al., 
2008; Fuchs et al., 2005; Preston, Heaton, McCann, Watson & Selke, 2009; Kaufmann & 
Nuerk, 2006). In addition, WM and Learning Disorder were found to contribute 
significant unique variance to academic achievement, which suggests that they may be 
separable, independently compromising the academic achievement of subgroups of 
adolescents with ADHD.

Our hypothesis that adolescents with ADHD and concurrent WMD would have 
greater severity of inattention symptoms was not confirmed. Moreover, we found that 
the inattention symptom dimension was not related to WM performance when 
controlling for the hyperactivity/impulsivity symptom dimension. Although these 
findings contradict previous research documenting associations between EFD and 
inattentive symptoms (Biederman, et al., 2004; Diamantopoulou et al., 2007), they are in 
line with a study by Loo et al. (2007), which showed no difference in severity of
inattention symptoms between adolescents with ADHD with and without EFD. Moreover, we did not find differences between adolescents with ADHD with and without WMD in the severity of other behavioural, emotional and social problems. Thus, our results suggest that adolescents with ADHD and WMD are not merely a more severe group, but rather a potentially unique group that may not be readily identifiable by traditional diagnostic probes, such as behavioural rating scales.

With regards to the contribution of inattention to academic achievement, we found that teacher ratings of inattention accounted for a significant amount of variance in math achievement, which is consistent with previous studies (Fuchs et al., 2006; Breslau et al., 2009a). By contrast, the finding that inattention did not significantly contribute to academic achievement in reading and spelling contradicts previous research (Breslau et al., 2009a; 2009b). Although the reasons for these discrepant findings are unclear, several possible explanations should be considered. One possibility may be related to methodological differences in the way inattention is operationalized and measured. For instance, a recent study showed that whereas parent-rated inattention did not predict significant variance in academic achievement, assessment through a standardized neuropsychological test of attention was a significant predictor of academic achievement across domains (Preston et al., 2009). Moreover, the same study found that attentional control/switching (i.e., changing attentional focus flexibly) predicted academic achievement across academic areas, but sustained attention (i.e., maintaining attention over an extended period of time) only predicted performance in math. Thus, it is also plausible that different aspects of attention may be associated differently with distinct
academic domains. Future research should seek to further clarify the relationships among WM, inattention and academic achievement in individuals with ADHD.

As regards to gender differences, we found that male and female adolescents with ADHD did not differ in terms of their WM functioning or academic achievement, which is broadly consistent with the previous ADHD literature (Gaub & Carlson, 1997; Gershon, 2002; Rucklidge & Tannock, 2001). There was also no evidence of gender differences as related to the severity of behavioural symptoms of inattention and hyperactivity/impulsivity, according to both parent and teacher ratings on the SWAN scales. In contrast, male and female adolescents with ADHD differed in their psychological adjustment. Whereas female adolescents with ADHD were rated by parents as having greater emotional symptoms and were more likely to be diagnosed with an Anxiety Disorder, male adolescents with ADHD exhibited greater externalizing problems as reported by teacher ratings. This latter pattern of findings is in line with a previous meta-analysis on gender differences in ADHD (Gershon, 2002). In addition, we did not find interaction effects in any of the outcome variables suggesting that WM performance and gender have independent effects on functional outcomes in adolescents with ADHD.

**Clinical Implications**

The findings from this study have important implications for the assessment and treatment of individuals with ADHD. The present results suggest that deficits in WM may account for the poor academic functioning of a subgroup of individuals with ADHD. Because these WM deficits may not be detected during standard clinical assessments of
ADHD using rating scales or symptom descriptions, neuropsychological evaluation of WM might be needed in order to identify a subgroup of individuals with ADHD at risk for academic problems. Our findings also suggest that WM should be considered as a treatment target. Improving WM through a combination of approaches that have been shown to enhance WM performance and academic achievement—such as pharmacological treatment (Bedard, Jain, Hogg-Johnson, & Tannock, 2007; Scheffler et al., 2009), working memory training (Holmes, Gathercole & Dunning, 2009; Klingberg et al., 2005), and academic interventions aimed at reducing WM loads in learning activities (Gathercole & Alloway, 2008), along with strategies to enhance academic skills (Jitendra, DuPaul, Someki, Tresco, 2008)—may help improve the academic achievement of this subgroup of individuals with ADHD.

**Limitations**

There are limitations to the current study that must be addressed. Firstly, due to the lack of a control group, our study design did not allow us to determine whether WM deficits have an independent effect on academic achievement, or whether they add or interact with ADHD symptoms to compromise the academic achievement of individuals with ADHD. That is, WMD may impact academic achievement differently in individuals with ADHD symptoms than in typically developing individuals. Future research should aim at replicating this study, but with the inclusion of a control group in order to compare rates of WMD in an ADHD vs. a control sample. Such a study could further clarify whether WMD combined with ADHD symptoms have a greater impact on academic functioning than that of poor WM alone. Secondly, to define WMD, we used
psychometric measures that assess WM under artificial, well-controlled conditions. In these conditions, the demands placed on WM were usually low and of short duration. Thus, our assessment of WM may lack ecological validity, and may not represent the demands placed on WM in everyday settings. Thirdly, in this study we only evaluated academic achievement through the use of a standardized test of basic academic skills. We did not provide a rigorous evaluation of higher-level academic skills such as advanced reading comprehension, math reasoning and written expression—academic tasks which are known to place high demands on WM, and which are more representative of the academic demands at the secondary level. Finally, our sample of adolescents with ADHD was clinically referred and of a restricted age range. Thus, we do not know to what extent our findings generalize to community samples of adolescents with ADHD and to other age groups.

Despite these limitations, our findings show that WMD is one of the factors that compromise the academic achievement of individuals with ADHD, and that these effects cannot be explained by other clinical features. In addition, findings from this study provide further support for the notion that ADHD is a heterogeneous disorder, and suggest that deficits in WM may partly explain the heterogeneity in functional outcomes documented in a subgroup of individuals with ADHD. Progress towards preventing and remediating the academic difficulties of such a subgroup may be made by alleviating their WM weaknesses.
Table 1
Demographic Characteristics, Psychiatric Comorbidity and Working Memory in Adolescents with ADHD, Stratified by Group

<table>
<thead>
<tr>
<th>Variables</th>
<th>ADHD (n=61)</th>
<th>ADHD + WMD (n=18)</th>
<th>df</th>
<th>$X^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gender</td>
<td>45 (74)</td>
<td>13 (72)</td>
<td>1</td>
<td>0.17</td>
</tr>
<tr>
<td>ADHD Medication Status</td>
<td>21 (34)</td>
<td>8 (44)</td>
<td>1</td>
<td>0.60</td>
</tr>
<tr>
<td>Oppositional Defiant Dis.</td>
<td>11 (18)</td>
<td>5 (28)</td>
<td>2</td>
<td>1.03</td>
</tr>
<tr>
<td>Conduct Disorder</td>
<td>3 (5)</td>
<td>3 (17)</td>
<td>1</td>
<td>2.65</td>
</tr>
<tr>
<td>Anxiety Disorders</td>
<td>12 (20)</td>
<td>3 (17)</td>
<td>2</td>
<td>1.07</td>
</tr>
<tr>
<td>Mood Disorders</td>
<td>1 (2)</td>
<td>1 (6)</td>
<td>2</td>
<td>1.28</td>
</tr>
<tr>
<td>Learning Disorders</td>
<td>18 (30)</td>
<td>7 (39)</td>
<td>1</td>
<td>0.50</td>
</tr>
<tr>
<td>Age (years)</td>
<td>15.40</td>
<td>14.72</td>
<td>77</td>
<td>1.806</td>
</tr>
<tr>
<td>Digit Span</td>
<td>11.02</td>
<td>7.11</td>
<td>77</td>
<td>5.24***</td>
</tr>
<tr>
<td>Letter-Number Sequen.</td>
<td>11.00</td>
<td>8.06</td>
<td>77</td>
<td>5.17***</td>
</tr>
<tr>
<td>Spatial Span</td>
<td>9.61</td>
<td>6.78</td>
<td>67</td>
<td>5.76***</td>
</tr>
<tr>
<td>Finger Windows</td>
<td>9.88</td>
<td>6.39</td>
<td>77</td>
<td>4.78***</td>
</tr>
</tbody>
</table>

Note. df = degrees of freedom; $X^2$ = Pearson’s Chi Square; t = t-test; ADHD = adolescents with ADHD with adequate WM; ADHD + WMD = adolescents with ADHD with WMD; df = 1 (“yes or no”); df = 2 (“yes, no and rule out”)

*** p < .001
Table 2

Academic Achievement in Adolescents with ADHD, Stratified by Working Memory Deficit (WMD) Group

<table>
<thead>
<tr>
<th>Academic Achievement</th>
<th>ADHD</th>
<th>ADHD + WMD</th>
<th>Univariate Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
</tr>
<tr>
<td>Broad Reading</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>108.13</td>
<td>13.71</td>
<td>96.17</td>
</tr>
<tr>
<td>Broad Math</td>
<td>97.90</td>
<td>12.04</td>
<td>90.72</td>
</tr>
<tr>
<td>Spelling</td>
<td>107.38</td>
<td>14.55</td>
<td>99.00</td>
</tr>
<tr>
<td>Cluster Subtests</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Letter Word Identification</td>
<td>107.25</td>
<td>9.63</td>
<td>99.00</td>
</tr>
<tr>
<td>Reading Fluency</td>
<td>109.15</td>
<td>17.20</td>
<td>98.44</td>
</tr>
<tr>
<td>Passage Comprehension</td>
<td>99.67</td>
<td>10.76</td>
<td>87.39</td>
</tr>
<tr>
<td>Calculation</td>
<td>98.18</td>
<td>16.29</td>
<td>87.44</td>
</tr>
<tr>
<td>Math Fluency</td>
<td>88.80</td>
<td>15.41</td>
<td>84.89</td>
</tr>
<tr>
<td>Applied Problems</td>
<td>101.02</td>
<td>7.24</td>
<td>96.50</td>
</tr>
</tbody>
</table>

Note. ADHD = adolescents with ADHD with adequate WM; ADHD + WMD = adolescents with ADHD with WMD; η² = Partial eta-square
<table>
<thead>
<tr>
<th>Symptoms of ADHD</th>
<th>ADHD</th>
<th>ADHD +WMD</th>
<th>Omnibus Test</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
</tr>
<tr>
<td>SWAN Parent</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inattention</td>
<td>1.71</td>
<td>0.58</td>
<td>1.46</td>
</tr>
<tr>
<td>Hyperactivity/Impulsivity</td>
<td>0.67</td>
<td>0.82</td>
<td>0.70</td>
</tr>
</tbody>
</table>

| SWAN Teacher                         |            |            |              |             |              |           |     |        |
| Inattention                          | 1.17       | 1.13       | 1.54         | 1.01        | .898          | 1.32      | .261 | .102    |
| Hyperactivity/Impulsivity            | 0.50       | 1.18       | 0.79         | 1.19        | .898          | 1.32      | .261 | .102    |

<p>| Psychological Adjustment             |            |            |              |             |              |           |     |        |
| SDQ Parent                           |            |            |              |             | .898          | 1.32      | .261 | .102    |
| Emotional Symptoms                   | 3.31       | 2.44       | 4.17         | 2.94        | .898          | 1.32      | .261 | .102    |
| Conduct Problems                     | 3.84       | 2.21       | 4.06         | 2.04        | .898          | 1.32      | .261 | .102    |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Hyperactivity-Inattention</td>
<td>7.48</td>
<td>1.90</td>
<td>7.00</td>
<td>2.30</td>
</tr>
<tr>
<td>Peer Problems</td>
<td>2.72</td>
<td>2.50</td>
<td>3.33</td>
<td>2.54</td>
</tr>
<tr>
<td>Prosocial Behaviour</td>
<td>6.49</td>
<td>2.32</td>
<td>7.56</td>
<td>1.82</td>
</tr>
<tr>
<td>Impact Score</td>
<td>3.70</td>
<td>2.15</td>
<td>4.17</td>
<td>2.50</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Wilks' $\lambda$</th>
<th>F (6, 67)</th>
<th>p</th>
<th>$\eta^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDQ Teacher</td>
<td>.943</td>
<td>0.67</td>
<td>.673</td>
<td>.057</td>
</tr>
<tr>
<td>Emotional Symptoms</td>
<td>2.27</td>
<td>2.07</td>
<td>2.53</td>
<td>2.53</td>
</tr>
<tr>
<td>Conduct Problems</td>
<td>2.1</td>
<td>1.15</td>
<td>3.53</td>
<td>2.53</td>
</tr>
<tr>
<td>Hyperactivity-Inattention</td>
<td>7.2</td>
<td>2.33</td>
<td>7.65</td>
<td>2.71</td>
</tr>
<tr>
<td>Peer Problems</td>
<td>2.29</td>
<td>2.30</td>
<td>2.59</td>
<td>2.60</td>
</tr>
<tr>
<td>Prosocial Behaviour</td>
<td>6.02</td>
<td>2.84</td>
<td>4.59</td>
<td>2.4</td>
</tr>
<tr>
<td>Impact Score</td>
<td>1.78</td>
<td>1.33</td>
<td>2.12</td>
<td>1.69</td>
</tr>
</tbody>
</table>

Note. ADHD = adolescents with ADHD with adequate WM; ADHD + WMD= adolescents with ADHD with WMD; Wilks' $\lambda$ = Wilks’ Lambda; $\eta_p^2$ = Partial eta- square; SWAN = Strengths and Weaknesses of ADHD-symptoms and Normal-behaviour scale; SDQ = Strengths and Difficulties Questionnaire.
<table>
<thead>
<tr>
<th>Variables</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. WM Composite</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Broad Reading</td>
<td></td>
<td>.455*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Broad Math</td>
<td></td>
<td>.482***</td>
<td>.517***</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Spelling</td>
<td></td>
<td>.293***</td>
<td>.747***</td>
<td>.610***</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. Parent Inattention</td>
<td></td>
<td>.137</td>
<td>.053</td>
<td>-0.061</td>
<td>-0.025</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. Teacher Inattention</td>
<td></td>
<td>-0.262*</td>
<td>-0.194</td>
<td>-0.322**</td>
<td>-0.132</td>
<td>0.139</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7. Parent Hyper/Impul</td>
<td></td>
<td>0.011</td>
<td>-0.012</td>
<td>0.107</td>
<td>0.019</td>
<td>0.669***</td>
<td>-0.058</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8. Teacher Hyper/Impul</td>
<td></td>
<td>-0.134</td>
<td>0.001</td>
<td>-0.021</td>
<td>0.097</td>
<td>0.167</td>
<td>0.455***</td>
<td>0.250*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9. Medication Status</td>
<td></td>
<td>0.054</td>
<td>-0.024</td>
<td>0.227*</td>
<td>0.056</td>
<td>0.022</td>
<td>-0.281*</td>
<td>0.130</td>
<td>-0.245*</td>
<td></td>
</tr>
<tr>
<td>10. Learning Disorder</td>
<td></td>
<td>-0.087</td>
<td>-0.358**</td>
<td>-0.357**</td>
<td>-0.464**</td>
<td>-0.083</td>
<td>0.228*</td>
<td>-0.224</td>
<td>0.068</td>
<td>-0.130</td>
</tr>
</tbody>
</table>

Note. * Point Biserial Correlation; WM composite = working memory average score for all working memory measures; Learning Disorder = Categorical variable (yes or no); Medication Status = Categorical variable (yes or no on medication for ADHD); Parent Inattention and Parent Hyperactivity/Impulsivity = Parent Ratings on the Strengths and Weaknesses of ADHD-symptoms and Normal-behaviour scale (SWAN); Teacher Inattention and Teacher Hyperactivity/Impulsivity = Teacher Ratings on the Strengths and Weaknesses of ADHD-symptoms and Normal-behaviour scale (SWAN)

*P < .05; ** P < .01; ***p < .001
Table 5
Hierarchical Regression Analysis of Working Memory as a Predictor of Academic Achievement in Adolescents with ADHD

<table>
<thead>
<tr>
<th>Variable</th>
<th>Broad Reading</th>
<th>Broad Math</th>
<th>Spelling</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ΔR²</td>
<td>ΔF</td>
<td>β</td>
</tr>
<tr>
<td>Step 1: Predictors</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Parent Inattention</td>
<td>0.23</td>
<td>1.47</td>
<td>-0.10</td>
</tr>
<tr>
<td>Teacher Inattention</td>
<td>-0.25</td>
<td>-1.87</td>
<td>-0.275</td>
</tr>
<tr>
<td>Parent Hyp/Imp</td>
<td>-0.29</td>
<td>-1.77</td>
<td>0.03</td>
</tr>
<tr>
<td>Teacher Hyp/Imp</td>
<td>0.16</td>
<td>1.17</td>
<td>0.17</td>
</tr>
<tr>
<td>Medication Status</td>
<td>-0.07</td>
<td>-0.61</td>
<td>0.15</td>
</tr>
<tr>
<td>Learning Disorder</td>
<td>-0.37</td>
<td>-3.16**</td>
<td>-0.29</td>
</tr>
<tr>
<td>Step 2: Predictor</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WM Composite</td>
<td>0.144</td>
<td>14.275***</td>
<td>0.195</td>
</tr>
</tbody>
</table>

Note. WM composite = working memory average score for all working memory measures; Parent Inattention and Parent Hyperactivity/Impulsivity = Parent Ratings on the Strengths and Weaknesses of ADHD-symptoms and Normal-behaviour scale (SWAN); Teacher Inattention and Teacher Hyperactivity/Impulsivity = Teacher Ratings on the Strengths and Weaknesses of ADHD-symptoms and Normal-behaviour scale (SWAN); Learning Disorder = yes or no dummy variable; Medication Status = on medication for ADHD, yes or no dummy variable on medication for ADHD.

*P < .05; ** P < .01; ***p < .001
CHAPTER THREE:

General Conclusions and Implications
3.1 Summary of Findings

The overall aim of the present thesis was to examine the impact of working memory deficits—a central EF process—on the academic achievement of adolescents with ADHD. In this study, adolescents with a clinical diagnosis of ADHD were subtyped into those with and without WMD based on impairment in at least two WM measures. Then, they were compared in terms of their academic achievement in reading, mathematics and spelling, as well as in other clinical characteristics. In addition, we examined the relationship between WM performance, academic achievement and other clinical features, and investigated the independent contribution of WM to the academic achievement of adolescents with ADHD over and above that of other clinical features.

The major findings from this study showed that adolescents with ADHD and concurrent WMD demonstrated significantly lower academic achievement across essential academic areas compared to adolescents with ADHD and adequate WM. Moreover, we found that adolescents with ADHD with and without WMD did not differ in other clinical characteristics, including severity of ADHD symptoms or psychological adjustment. These latter findings suggest that the impact of WMD on academic achievement in individuals with ADHD cannot be attributed to other clinical features associated with the disorder, nor to a more severe ADHD group. Further support for this finding was provided by results indicating a unique and significant contribution of WM performance to academic achievement in reading, mathematics and spelling, over and above that of other clinical features. Taken together, this pattern of results suggests that WMD is one of the factors compromising the academic achievement of a subgroup of
individuals with ADHD, and that these effects cannot be explained by other clinical features. Therefore, deficits in WM should be seen as a discrete cognitive comorbidity that may compromise the educational progress of a subgroup of individuals with ADHD.

3.2 Definition of Working Memory Deficits (WMD)

According to our categorical definition of WMD, 23% of adolescents with ADHD demonstrated deficits in WM. Although our definition of WMD was more liberal than previous studies subtyping individuals with ADHD based on EFD, it proved to have clinical relevance. Specifically, in this study, we defined a WMD as a scale score of 7 (16th percentile) or less on at least two standardized clinical measures of working memory span. By contrast, Loo et al. (2007) and Nigg et al. (2005) defined impairment in an EF measure as the lowest 10th percentile, whereas Biederman et al. (2004, 2006) used a 1.5 SD for normally distributed variables and the 7th percentile for non-normally distributed variables in at least two measures of executive functioning. Despite our broader cut-off, the validity of our categorical definition of WMD was partially supported by our findings. That is, our definition of WMD proved to be effective at identifying a subgroup of adolescents with ADHD who exhibited poorer performance in academic measures of reading, mathematics and spelling.

With regards to the percentage of adolescents with ADHD and WMD, we found that 23% of adolescents were classified as having a WMD, which is consistent with our hypothesis, as well as with previous findings on psychometrically defined EFD
(Biederman et al., 2004; Loo et al., 2007). However, it is important to note that we may be underestimating the magnitude of WM impairments in this population. In our study, we defined WMD using standardized, clinical measures of WM. These measures are administered in highly controlled settings in which there are limited distractions, and constraints are placed on the individual’s behaviour. Moreover, these WM span tasks demand WM resources for a brief period of time, using tightly controlled stimuli. Thus, performance on these measures may either exaggerate, or conversely, mask the true magnitude of an individual’s working memory capacity. That is, poor performance in these tasks may be only capturing WM weaknesses in the most severe cases that occur even under the most optimal conditions. Despite this limitation, our findings suggest that standardized, clinical tests of WM span commonly used in neuropsychological and psychoeducational assessments have clinical and predictive validity. That is, performance in these measures proved to relate to real-life performance in outcome measures of academic functioning.

As well, we recognize that our method of dichotomizing the number of tests impaired to create a categorical definition of WMD may result in some loss of information, and that a dimensional approach may better reflect the true distribution of this cognitive ability in the population. However, a binary definition of WMD with a specified clinical cut-off score could prove useful for clinicians as a potential screening tool for identifying individuals with ADHD at greater risk for academic failure, and thus could have clinical and practical implications. Future work should seek to further evaluate our proposed definition of WMD, and to investigate its ecological validity as well as its research and clinical utility.
3.3 Clinical Implications of Findings

The findings from this thesis have several practical implications for the understanding, assessment and treatment of individuals with ADHD. Firstly, in line with previous research on EFD in ADHD (e.g., Biederman et al., 2004, 2006; Nigg et al., 2005, Loo et al., 2007), results from this study show that not all individuals with ADHD have psychometrically defined deficits in WM. Therefore, WMD should not be seen as an essential feature or a diagnostic indicator of the disorder, but rather as a discrete cognitive comorbidity. Secondly, findings from this study showed that adolescents with ADHD with and without WMD did not differ in terms of other clinical features, such as severity of ADHD symptoms or other behavioural, emotional or social difficulties. These results suggest that adolescents with ADHD and comorbid WMD are not a more severe ADHD subgroup, but rather a potentially unique group which may not be identifiable during traditional diagnostic assessments, or through behavioural rating scales. Therefore, in order to identify this subgroup of individuals with ADHD which may be at greater risk for academic problems, evaluation of WM through psychometric testing or other forms of WM assessment may be necessary. Thirdly, results from this study indicate that adolescents with ADHD, as a group, may have greater difficulties with mathematics—particularly with math fluency—than with reading and spelling. Thus, it is possible that this academic area may need more intensive academic remediation. Finally, this study identifies WMD as a one of the factors constraining the
academic progress of a subgroup of individuals with ADHD, and identifies WM as a treatment target.

3.4 Working Memory Interventions

The findings from this study, together with previous research demonstrating WM impairments in ADHD (Martinussen et al., 2005) and associations between WM and academic achievement (Gathercole et al., 2004), suggest that WM should be considered a target for treatment in individuals with ADHD and WMD. There are several interventions that have been shown to improve working memory. Among these interventions are the following: pharmacological treatments, cognitive training of working memory, and academic interventions aimed at reducing working memory loads and improving academic skills. These interventions are briefly reviewed below.

Psychostimulant medications are the most widely used treatment for children with ADHD. Estimated prevalence of use rate among all Canadian children are of 1.6% (Charach, Cao, Schachar & To, 2006). Numerous studies have assessed the efficacy of methylphenidate, a catecholaminergic stimulant, for treating the core behavioural symptoms of ADHD in childhood and adulthood. These studies have shown positive results (MTA Cooperative Group, 1999). In recent years, evidence has emerged suggesting that stimulant medication can also enhance various executive function processes—including auditory-verbal and visual-spatial working memory—in children and adolescents with ADHD (Bedard, Martinussen, Ickowicz and Tannock, 2004;
Bedard & Tannock, 2008; Kempton et al., 1999; Mehta, Goodyer & Sahakian, 2004). For instance, a study by Barnett and colleagues (2001) comparing performance in spatial working memory tasks among unmedicated children with ADHD with that of medicated children with ADHD and of a control group, found that the performance of the unmedicated children was significantly lower than that of children in the control or medicated ADHD groups. Moreover, in a double-blind, within-subject, placebo-controlled trial of methylphenidate in children with ADHD, Mehta and colleagues (2004) found that a single dose of medication treatment improved performance in tasks involving working memory. Likewise, a randomized, placebo-controlled trial of methylphenidate in children and adolescents with ADHD found that methylphenidate had selective beneficial effects on working memory (Bedard et al., 2007). Specifically, medication improved visual-spatial storage and manipulation, and auditory-verbal manipulation but not auditory-verbal storage. Together, these studies show that stimulant medication can enhance working memory in children and adolescents with ADHD.

Even though stimulant medication has been shown to improve academic productivity (e.g., task completion) and academic accuracy in individuals with ADHD (Evans et al., 2001), research regarding medication effects on academic outcomes has not consistently shown gains (MTA Cooperative Group, 1999, 2004). However, some recent studies are beginning to demonstrate that medication treatment may lead to improvements in academic achievement. For instance, a study of children with ADHD in Taiwan reported that approximately 61-66% of their sample showed improved academic achievement in Chinese and arithmetic after 16 weeks of methylphenidate
treatment (Pinchen, Chung, Chen & Chen, 2004). Given that both Chinese language and arithmetic are dependent upon visuo-spatial WM, it is possible that improved academic achievement may have been mediated by the impact of medication on WM functioning. Furthermore, in a larger-scale, longitudinal study comparing the academic achievement of medicated and unmedicated children with ADHD over a period of 6 years (from kindergarten to Grade Five), it was found that medicated children’s mean scores were 2.9 points higher in mathematics (comparable to gains attained during 0.19 years over a 6-year period) and 5.4 points higher in reading (comparable to 0.29 years) compared to the scores of unmedicated children with ADHD (Scheffler et al., 2009). In another prospective longitudinal study examining the effects of medication treatment on long-term academic outcomes (9 years follow-up) in adolescents and young adults, Powers and colleagues (2008) compared medicated children to unmedicated children, and found that medication treatment improved academic outcomes in terms of academic achievement measures and school GPA. However, both ADHD groups still demonstrated poorer academic outcomes compared to a non-ADHD group (Powers, Marks, Miller, Newcorn, & Halperin 2008). Collectively, these studies indicate that medication treatment may have positive effects on working memory and academic achievement, but that medication treatment does not regularize performance to the same level of typically developing children. On the other hand, successful treatment of ADHD with stimulant medication is likely to improve WM in ways that may enhance readiness to acquire academic skills through targeted academic interventions. Further research should empirically examine whether the link between medication treatment and academic outcomes is partly mediated by enhanced WM functioning.
Cognitive training of WM has also been shown to improve WM skills. For example, in a study by Wexler and colleagues (2000), eight adults with schizophrenia who had deficits in auditory-verbal WM performed daily verbal memory exercises that became progressively more difficult over a 10-week training period. Performance in auditory-verbal WM improved after training, and gains were maintained at follow-up (six weeks after training; Wexler, Anderson, Fulbright & Gore, 2000). Working memory performance has also been found to be substantially enhanced by computerized WM training. Computerized working memory training uses an adaptive staircase method in which the difficulty level is automatically and continuously adapted to the performance of the child, in order to optimize the training effect. In this type of training, the child works at their maximum WM capacity on a near-daily basis for approximately 35 minutes a day for five to six weeks, in a high-quality graphics environment with multiple motivational features. A double-blind, placebo-controlled study using this intensive computerized training of WM over a 5-6 week period with a sample of 14 children with ADHD showed that the treatment group improved their WM skills compared to those children using a placebo non-adaptive computerized program (Klingberg, Forssberg & Westerberg, 2002). This improvement in WM was not only found in practiced tasks but also in non-practiced and not computerized WM tasks, as well as in a non-trained reasoning task (Klingberg et al., 2002), which suggests that the training effect generalized to other contexts. In a similar study, 53 children with ADHD were randomly assigned to either the computerized adaptive WM training program, or to the placebo non-adaptive program, and they were evaluated at pre- and post- treatment, as well as at a 3-month follow-up (Klingberg et al., 2005). Results demonstrated that the children
who undertook high intensity training of WM improved significantly more than the placebo group in both visual-spatial and auditory-verbal measures of WM. They also improved significantly in tasks assessing response inhibition and reasoning at both post-intervention and at follow-up. Moreover, in a recent placebo-controlled study investigating the effects of this computerized WM training on children with low WM, it was found that children who completed the adaptive WM treatment program showed significant improvement in both verbal and visual-spatial WM as assessed by a well-established standardized battery of untrained WM tasks, and also by a classroom analogue test of WM, with these effects being maintained at 6 month follow up (Holmes et al., 2009). Moreover, the group receiving the adaptive WM training program showed significant gains on academic tests of math reasoning 6 months after training. Thus, preliminary evidence suggests that WM training may translate into academic gains in the long-term. However, more work is still needed to further evaluate the long-term impact of WM training on academic outcomes in individuals with ADHD.

Classroom-based strategies targeted at reducing WM loads in learning activities may also be used to improve learning. Children and adolescents with ADHD and WMD may struggle in the classroom because they are unable to meet the memory demands of many structured learning activities (Gathercole & Alloway, 2008). They may forget lengthy instructions, make place-keeping errors, miss letters or words in sentences and/or fail to cope with simultaneous storage and processing demands that are beyond their WM capacity (Alloway & Gathercole, 2006). Levine (1999) suggested intervention approaches for children who experience impairments in WM. For example, teachers could stress completing one task at a time, develop a stepwise approach to academic
tasks, or use checklists to indicate stages of completion. Each of these strategies allows information to be chunked, thereby minimizing demands on WM. The use of visual models, considerable repetition of verbal explanations, and the integration of computer software with its predominantly visual-spatial mode of presentation, could also help to reduce the load on WM (Martinussen, Tannock, McInnes & Chaban, 2006). Children and adolescents with ADHD and WMD might also benefit from developing effective coping strategies to deal with situations in which they experience working memory failures. Such coping strategies may include asking for forgotten information when necessary and learning to use memory aids (Gathercole & Alloway, 2008). The efficacy and practical impact of these classroom-based strategies on learning and academic progress still must be fully evaluated. Future studies should examine whether consistent use of these strategies help improve the academic achievement of children and adolescents with ADHD and WMD.

In addition to these WM interventions, academic interventions aimed at directly improving academic skills in content areas such as reading and mathematics are critical if we are to improve the academic achievement of students with ADHD. Academic approaches which have been developed and have gained some preliminary support for use with children and adolescents with ADHD include the following: peer and parent tutoring, task and instructional modifications, computer assisted instruction, strategy training, self-monitoring and homework management programs (for a review see DuPaul & Eckert, 1998; Raggi & Chronis, 2006). Reading interventions which focus on basic reading skills (e.g., decoding, phonological awareness and alphabetic understanding), reading accuracy (e.g., repeated reading) and higher-level reading comprehension (e.g.,
collaborative strategic reading or generating questions) have also been shown to improve academic skills in individuals with ADHD (Jitendra et al., 2008). Empirically supported techniques for improving mathematics focus on promoting basic math facts and computational skills, as well as improving higher-level cognitive skills (e.g., schema-based instruction) involved on word problem-solving (Jitendra et al., 2008). Given the lack of evidence favoring one specific WM and academic intervention, a combination of approaches aimed at improving working memory and academic skills may be ideal in order to improve the educational progress of individuals with ADHD and WMD.
APPENDIX A:

Additional Work
A.1 Statistical Analysis

In order to further examine the academic achievement of adolescents with ADHD, we calculated the percentage of adolescents with ADHD performing 1 SD ($\leq 85$) or below the standardization sample mean of 100 in Broad Reading, Broad Math and Spelling, as well as in the subtests comprising the Broad Reading and Broad Math Clusters. First, we calculated the number and percentage of adolescents with ADHD scoring 1 SD below the mean in the overall sample of adolescents. Then, we compared adolescents with ADHD with adequate WM to adolescents with ADHD with WMD in terms of the proportion of participants in each group scoring -1 SD or below the mean of 100. To conduct this analysis, test scores were coded as the following: a standard score of 85 or less was coded as a “1”, and a standard score of 86 or more was coded as “0”. This procedure was performed for each Cluster and each subtest of the WJ-III. Then, the frequency of adolescents with a score of 1 (85 standard score or below) was calculated for the overall sample and for each WMD group. Finally, Chi-Square ($X^2$) tests were used to compare adolescents with ADHD with adequate WM to adolescents with ADHD with WMD.

A.2 Results

The number and percentage of adolescents with ADHD in the overall sample scoring 1 SD below the mean were the following: four (5%) in Broad Reading, eighteen
(23%) in Broad Math, and seven (9%) in the Spelling subtest. When examining the subtests comprising the Broad Reading and Broad Math Cluster, the following number and percentage of adolescents with ADHD performed 1 SD below the mean: one (1%) in Letter-Word Identification, six (8%) in Reading Fluency, eight (10%) in Passage Comprehension, twenty-two (28%) in Calculation, forty-two (53%) in Math Fluency and zero (0%) in Applied Problems. The number and percentage of adolescents with ADHD performing 1 SD or below on all academic achievement tests, stratified by WMD group are presented in Table A.1. As shown in Table A.1, there were no significant differences between groups in the rate of adolescents performing -1 SD below the standardization sample mean of 100 in Broad Reading, Broad Math or Spelling. The difference between groups in Broad Math approached statistical significance (p = .064), with a greater proportion of adolescents with ADHD and WMD (39%) scoring -1 SD below the mean than adolescents with ADHD with adequate WM (18%). Inspection of impairments on component subtests (Letter-Word Identification, Reading Fluency, Calculation, Math Fluency, and Applied Problems), revealed a significant difference in the rate of adolescents scoring at or below a standard score of 85 in the Passage Comprehension subtest, with a greater proportion of adolescents with ADHD and concurrent WMD scoring -1 SD below the mean.

A.3 Discussion

The main finding from this analysis was that, in the overall sample of adolescents with ADHD, few adolescents with ADHD scored -1 SD below the mean in reading and
spelling, but a greater proportion did so in mathematics. This finding further suggests that individuals with ADHD, as a group, may have greater difficulty with mathematics. However, it is important to note that if we consider performance below an 85 standard score in these standardized tests of academic achievement as an area of academic difficulty, we may be underestimating the range of academic problems in adolescents with the disorder. This is because this test only assesses basic academic skills, which are not representative of the more complex, heavier academic demands placed on students at the secondary level.

The finding that a large proportion of adolescents with ADHD scored -1 SD below the mean in mathematics is not surprising given previous research documenting mathematics difficulties in individuals with the disorder, including greater math disabilities, than in the general population (Capano, Minden, Chen, Schachar & Ickowicz, 2005; Mayes & Calhoun, 2006). However, it is striking that more than half of the sample of adolescents with ADHD demonstrated difficulty with the Math Fluency subtest, and demonstrated difficulty to a lesser extent with the Calculation subtest, as compared to the Applied Problems math task. In the Math Fluency task, participants are required to solve basic arithmetic calculations (e.g., simple addition, subtraction, and multiplication) quickly and accurately within a 3-minute time limit, whereas in the Applied Problems subtest participants are required to solve applied math reasoning problems. This latter subtest is not timed and is presented both orally and in writing. Thus, this pattern of findings further indicates that the math difficulties of individuals with ADHD may lie in delayed automaticity of basic math facts and/or weaknesses in procedural knowledge, rather than in problems with math reasoning skills (Mather &
Jaffe, 2002). Another possibility is that distractibility and difficulty sustaining attention may have compromised performance on the Math Fluency task, as this task requires quick and careful identification of the operation signs. This explanation is consistent with our finding that teacher ratings of inattention predicted math performance, and is also consistent with previous research documenting associations between inattention and mathematics achievement (Fuchs et al. 2005; 2006). In addition, given the nature of the Math Fluency task (i.e., timed, quick retrieval of math facts), the performance of individuals with ADHD on this task may be impaired, because of greater demands placed on WM and other cognitive processes underlying math performance which have also been shown to be impaired in ADHD (Berg, 2008; Martinussen et al., 2005; Passolunghi, Marzocchi & Fiorillo, 2005; Kaufmann & Nuerk, 2006, 2008; Swanson & Beebe-Frankenberg, 2004).

With regards to group differences, we found that adolescents with ADHD with and without WMD did not differ significantly on most academic tests in terms of the percentage of adolescents in each group scoring -1 SD below the mean. However, there was a greater proportion of adolescents with ADHD and WMD scoring below an 85 standard score in the Passage Comprehension subtest. This subtest assesses reading comprehension, a task known to rely heavily on working memory (Baddeley, 2003; Just & Carpenter, 1992). Although a greater proportion of adolescents with ADHD and WMD scored -1 SD below the mean in Broad Math, the difference between groups did not reach statistical significance. Together, these findings suggest that group differences in academic achievement between adolescents with ADHD with and without WMD may not be detected by this method of evaluating academic performance. These differences
may be better captured by score differences. It is important to note, however, that a main limitation of this analysis was the small number of participants in each cell and expected frequency counts of less than 5, which may have resulted in loss of statistical power to detect differences between adolescents with ADHD with and without WMD.
### Table A.1

Number and Percentage of Adolescents with ADHD with and without WMD Scoring 1 SD (≤85) or Below the Standardization Sample Mean of 100 in Academic Achievement Tests

<table>
<thead>
<tr>
<th>Academic Achievement</th>
<th>ADHD</th>
<th>ADHD+WMD</th>
<th>Chi-Square df (1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Broad Reading</td>
<td>3</td>
<td>1</td>
<td>0.012 0.914</td>
</tr>
<tr>
<td>Broad Math</td>
<td>11</td>
<td>7</td>
<td>3.44 0.064</td>
</tr>
<tr>
<td>Spelling</td>
<td>4</td>
<td>3</td>
<td>1.76 0.185</td>
</tr>
<tr>
<td>Letter-Word Identification</td>
<td>0</td>
<td>1</td>
<td>3.43 0.064</td>
</tr>
<tr>
<td>Reading Fluency</td>
<td>3</td>
<td>3</td>
<td>2.73 0.098</td>
</tr>
<tr>
<td>Passage Comprehension</td>
<td>2</td>
<td>6</td>
<td>13.79 0.001</td>
</tr>
<tr>
<td>Calculation</td>
<td>15</td>
<td>7</td>
<td>1.41 0.234</td>
</tr>
<tr>
<td>Math Fluency</td>
<td>32</td>
<td>10</td>
<td>0.054 0.817</td>
</tr>
<tr>
<td>Applied Problems</td>
<td>0</td>
<td>0</td>
<td>-- --</td>
</tr>
</tbody>
</table>

Note. $X^2$ = Pearson’s Chi Square; Results of the Chi-Square test should be viewed with caution given the small number of participants in each cell; Results remained unchanged when the Likelihood Ration statistic and the Yates’ Continuity Correction were examined.
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