ATTENTION-DEFICIT/HYPERACTIVITY DISORDER (ADHD), WORKING MEMORY AND HYPERACTIVITY: AN EXAMINATION OF CORE PROCESSES IN LATE ADOLESCENTS AND ADULTS

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CHAPTER I

INTRODUCTION

Attention-deficit/hyperactivity disorder (ADHD) is characterized by inattention, hyperactivity and impulsivity (Barnett et al., 2001), and differentiated into three subtypes – Predominantly Inattentive (ADHD-I), Predominantly Hyperactive-Impulsive (ADHD-H), and Combined (ADHD-C; Proctor & Prevatt, 2009). ADHD was originally conceptualized as a disorder of childhood due to relatively low prevalence rates reported in adult relative to child studies (Fayyad et al., 2007), and a colloquial belief that most children eventually outgrew the disorder and associated impairments (Resnick, 2005). More recent studies provide strong evidence that ADHD persists into adulthood in 36.3 to 70% of individuals (Biederman, Mick, & Faraone, 2000; Polanczyk et al., 2007; Weisler & Goodman, 2008), suggesting upwards of 4 to 5% of the adult population meet criteria for the disorder (Kessler et al., 2006; Weisler & Goodman, 2008; Clarke, Heussler, & Kohn, 2005; Barkley, Fischer, Smallish, & Fletcher, 2002). Prevalence of ADHD subtypes in adults affected with the disorder show a pattern similar to childhood, with ADHD-C most prevalent (56%), followed by ADHD-I (37%) and ADHD-H (2%; Millstein, Wilens, Biederman, & Spencer, 1997).

Hyperactivity is a key symptom for subtype classification and is a primary reason for clinical referral due to the often disruptive nature of hyperactive behaviors (Sayal, Taylor, Beecham, & Byrne, 2002). The presence of hyperactive/impulsive symptoms is associated with the most severe impairment (Gaub & Carlson, 1997; Graetz, Sawyer, Hazell, Arney, & Baghurst, 2001; Faraone, Biederman, Weber, & Russell, 1998; Hinshaw, 2002) and is predictive of criminal activity in adulthood (Babinski, Hartsough, & Lambert, 1999). Hyperactive and impulsive symptoms often become apparent before age 5 (Taylor et al., 2004) resulting in clinical referral at a younger age than children with predominantly inattentive symptoms (Lahey et al., 1994). Preschool-aged boys with pervasive hyperactivity problems are more likely to annoy others, violate social rules, show less prosocial behavior, be less accepted by peers, and exhibit withdrawn behaviors (e.g., avoiding peers) as well as be disruptive, aggressive and disengagement in the classroom (Keown & Woodward, 2006). While some findings suggest that symptoms of hyperactivity remediate during adulthood (Biederman et al., 2000; Wilens, Biederman, & Spencer, 2002; Faraone, Biederman, & Mick, 2006), opposing findings suggest that adults diagnosed with ADHD in childhood continue to exhibit increased motor movement whether or not they continue to meet diagnostic criteria for ADHD (Halperin et al., 2008).

CHAPTER II

REVIEW OF LITERATURE

Hyperactivity in Theoretical Models of ADHD

Several prominent models of ADHD describe hyperactivity as a ubiquitous feature of the disorder resulting from impairment in inhibition processes (Barkley, 1997), anomalies in the caudate nucleus (Halperin & Schulz, 2006), or motivation to escape or avoid delay (Sonuga-Barke, 2002). The working memory model of ADHD, in contrast, hypothesizes that working memory deficits, particularly in the domain-general central executive, serve as a core feature, or endophenotype (Castellanos & Tannock, 2002), that underlies characteristics of the ADHD phenotype (Rapport, Chung, Shore, & Isaacs, 2001; Rapport et al., 2008). Specifically, the working memory model posits that biological influences (e.g., genetics, prenatal factors) contribute to alterations of neurobiological systems (e.g., dopamine dysregulation, cortical underarousal) that result in the observed deficits in working memory processes. Working memory involves the temporary storage and active manipulation of internal information and is comprised of a domain-general central executive and two subservient subsystems—the phonological loop (associated with storage and rehearsal of verbal information) and the visuospatial sketchpad (associated with storage and rehearsal of visual and spatial information; Baddeley, 2007). Motor activity is hypothesized as a compensatory mechanism that improves working memory performance by increasing cortical arousal to a level that will meet the increasing environmental demands on central executive functioning (Rapport et al., 2009).

Working Memory Deficits and ADHD-Related Hyperactivity

Efforts to examine and explicate ADHD-related activity have been predominantly confined to studies of children. For example, Rapport and colleagues (2009) identified a functional relationship between motor activity and working memory, such that increased ADHD-related motor activity was functionally related to increased demands on the working memory system, particularly the central executive. A more recent study found that motor activity in children with ADHD disproportionately increased relative to typically developing children during tasks that placed greater demands on focused attention associated with the central executive, rather than inhibitory processes (Alderson, Rapport, Kasper, Sarver, & Kofler, 2011). Collectively, these findings suggest that working memory processes are upstream of inhibition processes and provide support for the working memory model of ADHD (Rapport et al., 2001), which argues that deficits in working memory produce impairments in behavioral inhibition as well as increases in activity level.

Examination of the association between working memory and hyperactivity in adults with ADHD is particularly important since the ADHD phenotype appears to change during adulthood (i.e., presence of hyperactive symptoms decreases) while working memory deficits persist (Murphy, Barkley, & Bush, 2001; Schweitzer et al., 2006; Dige, Maahr, & Backenroth-Ohsako, 2010; Gansler et al., 1998). A comprehensive model of ADHD must adequately account for ontological variation in the ADHD phenotype and relate changes to potential endophenotypes (i.e., working memory) across the lifespan. Previous investigations of working memory and activity in adults with ADHD have been mostly limited to comparisons of subtypes (i.e., ADHD-C and ADHD-H/I versus ADHD-I) and subjective measures of activity. Extant findings have been relatively equivocal, suggesting that working memory impairments may be a general deficit associated with ADHD, and preclude conclusions regarding the functional relationship between activity level and working memory (Dige et al., 2010; Dowson et al., 2007; Gansler et al., 1998; Murphy et al., 2001; Schweitzer et al., 2006). For an extended review of current literature, refer to the Appendix.

Only one study to date has investigated the relationship between working memory and objectively measured ADHD-related motor activity in adults. Lis and colleagues (2010) examined motor activity during an n-back working memory task in adults with ADHD and healthy controls and found that impaired task performance was significantly associated with an increase in objectively measured activity level for adults with ADHD but not for healthy controls. The authors' conclusion that increased motor activity is associated with cognitive impairments in adults with ADHD may be premature, however, and should be tempered given several limitations. For example, the study's diagnostic/grouping procedure relied solely on self-report ratings of retrospective childhood and current symptoms. Adults with ADHD, however, tend to underreport symptom presence and severity, and have difficulty with retrospective recall (Kooij et al., 2008; McGough & Barkley, 2004; Smith, Pelham, Gnagy, Molina, & Evans, 2000). In addition, Lis and colleagues' use of a 1-back task (essentially a 2-choice recognition task) does not allow for examination of potential between-group storage/rehearsal differences (e.g., 1, 2 or 3-back load) or the contribution of specific component processes (e.g., storage/rehearsal and CE) associated with activity changes. Furthermore, the *n*-back task used by Lis and colleagues does not allow for examination of PH working memory processes, or cross-modality (e.g., phonological and visuospatial) comparisons. Examination of both phonological and visuospatial modalities is important in order to extend findings in children that revealed greater activity levels during the PH conditions (compared to VS conditions) with excessive activity primarily related to the contribution of the central executive (Rapport et al., 2009). Moreover, motor activity was measured by assessing displacement from a center point at regular intervals with an infrared motion analysis detector attached to the participant's head. This assessment of motor activity may underestimate activity by discounting movements limited to extremities (not necessarily associated with head movement) or overestimate activity by including postures with head displacement (not necessarily associated with gross motor activity; Rapport, Kofler, & Himmerich, 2006; Teicher, Ito, Glod, & Barber, 1996). Finally, Lis and colleagues' failure to include a control condition limits conclusions regarding the nature of hyperactivity in ADHD as ubiquitous or context-dependent.

Current Study

The current study is the first to examine whether activity level is functionally related to working memory demands associated with the central executive and storage/rehearsal components of working memory in adults with ADHD. The use of actigraphy and a working memory task with variable working memory demands has not previously been utilized with adults to investigate this relationship. Actigraphy provides an objective measure of gross motor activity that improves upon the use of subjective rating scales and other mechanical measures (e.g., infrared motion analysis). The current study also improves previous methodological procedures (Lis et al., 2010) through the use of collateral informants for childhood behaviors and a clinical interview to rule-out alternative diagnoses that may account of symptoms of ADHD (e.g., difficulty concentrating, restlessness). Finally, this is the first study of adults with ADHD to include phonological and visuospatial working memory tasks and control conditions, and therefore, the first study to examine the functional relationship between activity level and working memory demands.

Consistent with the working memory model of ADHD (Rapport et al., 2001), young adults with ADHD were expected to exhibit higher levels of activity during working memory tasks, relative to typically-developing peers, based on existing evidence of persistent neurocognitive deficits that decline but do not extinguish with age (Hervey, Epstein, & Curry, 2004). Activity level was expected to be higher for all participants during tasks that place demands on the phonological rather than visuospatial system, and disproportionately higher for participants with ADHD. This prediction is based on previous meta-analytic (Martinussen, Hayden, Hogg-Johnson, & Tannock, 2005) and experimental (Rapport et al., 2008; 2009) findings that report deficits in both working memory systems and a functional relationship between working memory demands and activity level in children. Finally, the central executive (CE) was predicted to provide the greatest contribution to activity level, while the phonological and visuospatial storage/rehearsal subsystems were not expected to contribute to activity level in either group after controlling for the CE.

CHAPTER III

METHODOLOGY

Participants

Participants were undergraduate students participating as a class requirement and community members participating to receive an ADHD screening. The sample consisted of 14 (7 male) participants with ADHD and 14 (8 male) typically developing (TD) participants. Participants were predominantly Caucasian (85%) and an average of 19.61 (SD=1.75) years old. Sample characteristics are displayed in Table 1.

Group Assignment

All participants were administered the Schedule for Affective Disorders and Schizophrenia-Present and Lifetime Version (K-SADS-PL; Kaufman et al., 1997), a detailed, semi-structured clinical interview that assesses symptom presence and severity. Participant profiles (including clinical interview and rating scales) were reviewed with a second clinician and the directing clinical psychologist to confirm diagnoses (if applicable) and to determine group assignment.

Participants in the ADHD group met the following criteria: (1) diagnosis by the directing clinical psychologist at the Center for Research of Attention and Behavior (CRAB) using DSM-IV-TR criteria for ADHD based on a K-SADS-PL interview with the participant and questionnaire profile; (2) symptom count of at least 4 items (from the Inattentive or Hyperactive-Impulsive symptoms) on the Barkley ADHD Current Symptoms Scale – Self-Report (Barkley & Murphy, 2006); (3) symptom count of at least 6 (from the Inattentive or Hyperactive-Impulsive symptoms) on the Barkley ADHD Childhood Symptoms Scale – Other Report (Barkley & Murphy, 2006) completed by a parent/guardian; and (4) no indication of current comorbid conditions based on supplemental ratings scales, a mental health history questionnaire, and clinical interview. Collateral ratings were obtained to allow for a multidimensional diagnostic approach and to account for underreporting observed in adults with ADHD (Kooij et al., 2008).

Participants included in the typically developing group had: (1) no evidence of any clinical disorder and normal developmental history based on participant K-SADS-PL interview; (2) symptom count scores less than 4 on the Barkley ADHD Current Symptoms Scale – Self-Report; (3) symptom count on collateral ratings within the non-clinical range (less than 6) on the Barkley ADHD Childhood Symptoms Scale – Other Report; and (4) no indication of other conditions based on supplemental ratings scales, mental health history questionnaire, and clinical interview.

Participants that presented with (a) gross neurological, sensory, or motor impairment, (b) history of a seizure disorder, (c) psychosis, or (d) Full Scale IQ score less than 85 were excluded from the study. Participants were asked to discontinue use of psychostimulant medication for 24 hours prior to the laboratory-based session.

Measures

Clinical Interview. The K-SADS-PL was designed to assess the presence, onset, course, duration, severity, and impairment of symptoms presented in the DSM-IV. Both current and past episodes of psychopathology were evaluated based on child/adolescent and parent reports. Interrater agreement (0.93 to 1.00), test-retest reliability (0.63 to 1.00), and concurrent validity (with parent rating scales) have been well-established with children (Kaufman et al., 1997). Although the K-SADS was originally developed for use with children, it has been successfully adapted for use with adults to measure past and present symptoms of psychopathology with reliability ranging from 0.70 to 0.90 and strong construct and criterion validity (Ambrosini, 2000; Belendiuk, Clarke, Chronis, & Raggi, 2007; Magnússon et al., 2006). The K-SADS-PL questions were adapted to suit an adult population by reframing probes in the past tense and using age-appropriate behavior examples, consistent with previous studies (Belendiuk et al., 2007; Magnússon et al., 2006).

ADHD Ratings Scales. The Barkley (Barkley & Murphy, 2006) report forms (Current Symptoms Scale – Self-Report and Childhood Symptoms Scale – Other Report) require participants and collaterals to rate the participants' behavioral and emotional problems based on DSM-IV criteria using a 4-point Likert scale. The scale assesses event frequency and ranges from 0 (never/rarely) to 3 (very often), with endorsement of 2 (often) or 3 considered clinically significant and included in symptom count totals. Developmentally referenced criterion cutoffs (four of nine symptoms) were implemented based on previous findings that thresholds used for children (six of nine symptoms) may be too restrictive for adults (Heiligenstein, Conyers, Berns, & Smith, 1998; Murphy & Barkley, 1996). Each of the scales contains 18 items assessing DSM criteria for symptoms of inattention and hyperactivity/impulsivity. The scales further differentiate ADHD symptoms from other disruptive behavior disorders with the inclusion of 8 questions assessing Oppositional Defiant Disorder and 15 questions assessing Conduct Disorder. Impairment is assessed by 10 additional questions (8 on the Childhood Symptoms Scales) that inquire about disruption in common settings (e.g., work, school, relationships). The Barkley ratings scales are widely used to assess ADHD psychopathology and have internal reliability coefficients ranging from .84 to .95 (Katz, Petscher, & Welles, 2009; Zucker, Morris, Ingram, Morris, & Bakeman, 2002) and strong discriminant validity (Barkley, Murphy, DuPaul, & Bush, 2002).

Intellectual Functioning. All participants were administered the Kaufman Brief Intelligence Test-Second Edition (KBIT-2; Kaufman & Kaufman, 2004) to obtain an overall estimate of intellectual functioning. The KBIT-2 is comprised of three subtests (Verbal Knowledge, Riddles, Matrices) from which two Standard Scores (Verbal, Nonverbal) and one overall score (IQ Composite) are derived. Scores have a mean of 100 and a standard deviation of 15. The Verbal score assesses verbal concept formation, reasoning ability and range of general knowledge. The Nonverbal score assesses visual processing and the ability to solve novel problems. The IQ Composite score provides a measure of comprehensive ability and general intelligence. Across derived scores, internal-consistency reliability ranges from .89 to .96 and test-retest reliability ranges from .76 to .93 depending on age group (Kaufman & Kaufman, 2004). Assessment of the validity of the KBIT-2 shows strong relationships with other measures of intelligence as well as expected correlations with measures of achievement (Kaufman & Kaufman, 2004). Concurrent validity for the KBIT-2 has been established with strong correlations (r = .89) between the IQ Composite and FSIQ on the Wechsler Abbreviated Scale of Intelligence (WASI) and the Wechsler Adult Intelligence Scale (WAIS-III). An intelligence measure was included to ascertain a general measure of intelligence to exclude participants with IQs below 85.

Background/Psychosocial History. A series of questionnaires designed to assess psychosocial history in adults (Barkley & Murphy, 2006) were completed by participants. Participants reported on information such as developmental history (i.e., developmental milestones/delays), medical and mental health history (i.e., illnesses, injuries, previous psychological diagnoses and treatment), social history (i.e., experiences of interpersonal relationships, traffic violations) and work history (i.e., reasons for employment termination). This information was gathered as part of a larger study and to provide additional historical documentation of reported symptoms and potential impairment.

Activity. MicroMini-Motionlogger® (Ambulatory Monitoring Inc., 2010) actigraphs are wristwatch-like devices that measure motor activity by recording frequency, intensity and duration of movement 16 times per second. The actigraphs were attached with a Velcro strap immediately above the participant's left and right ankles and onto his/her non-dominant wrist. An actigraph was not placed on the dominant hand in order to exclude activity associated with task response. Trunk placement is a common measurement site but was excluded in the current study given the increased sensitivity of these devices and more accurate representation of movement at the extremities (Eaton, McKeen, & Saudino, 1996). Participants were informed that the actigraphs' purpose is to record physiological data but no additional explanation was provided. All actigraphs were set on the Proportional Integrating Measure (loPIM) mode, which provides a measure of the participant's movement intensity (i.e. gross activity level) by registering an electrical current created when the instrument is moved. The current passes through an amplifier and filter to provide a histogram of recorded movement aggregated into one minute epochs for analysis (see Rapport et al., 2006) using the Action4 software program (Ambulatory Monitoring Inc., 2010). For each participant, activity rates were calculated for each task by summing data from all three actigraphs. Live observation software (The Observer XT; Noldus Information Technology, 2008) was used to record time stamps for each task that was then matched to corresponding time stamps within the actigraph data.

Actigraphs are reliable and valid (Tryon, 2005; Tryon & Williams, 1996; Pate, Almeida, McIver, Pfeiffer, & Dowda, 2006) and have estimated test-retest reliability (on the same physical site) ranging from 0.90 to 0.99 (Tryon, 2005; Tryon, 1985). Actigraphs have been used as an objective measure of activity in studies examining children with ADHD (Rapport et al., 2009), adolescents with chronic pain (Long, Palermo, & Manees, 2008) and adult ADHD smokers (Gehricke, Hong, Whalen, Steinhoff, & Wigal, 2009).

Phonological (PH) Working Memory Task. The phonological WM task was programmed using SuperLab 4.0 (Abboud, Schultz, & Zeitlin, 2008) and is similar to the Letter-Number Sequencing subtest in the Wechsler series of intelligence tests (Wechsler, 2008). The task was developed by Rapport and colleagues (Rapport et al., 2008) and is designed to assess phonological WM based on Baddeley's (2007) model. Participants heard the computer present a series of single digit numbers and one capital letter taken from a pre-recorded stimulus bank. Each stimulus (letter or number) was followed by a 200 ms interstimulus interval. Each trial was followed by a click and an image of a green light to indicate to the participant to respond. Trials ranged in set size from three stimuli to seven stimuli, but the letter never appeared in the first or last position of the series to reduce potential primacy or recency effects. The stimuli letter and serial position (i.e.

position 2, 3, 4, 5, or 6) was counterbalanced across trials to occur equally. Participants were instructed to recall the numbers aloud in order from smallest to largest followed by the letter. For example, if the trial 3 7 K 4 was presented, the correct response would be 3 4 7 K. Figure 1 provides a visual schematic of the PH task. Participants' verbal responses were independently coded by two research assistants in an adjacent room (outside the participant's view). The participant touched the computer screen to advance through the 24 trials (at each set size) of the task. Practice trials were administered prior to experimental trials, and the participant was required to respond correctly to 80% of the practice trials to proceed.

Visuospatial (VS) Working Memory Task. The visuospatial WM task was programmed using SuperLab 4.0 (Abboud, Schultz, & Zeitlin, 2008). The task is designed to assess visuospatial WM based on Baddeley's (2007) model and is based on the task established by Rapport and colleagues (Rapport et al., 2008). A series of 2.5 cm diameter dots (3, 4, 5, 6 or 7) was presented to participants sequentially for 800 ms in one of nine 3.2 cm squares arranged in three offset columns (to reduce the potential for phonological coding by assigning numeric values to the square locations). One dot was red, but the rest were black. No two dots appeared in the same square during a trial, and the red dot was never the first or last stimulus presented in order to minimize potential primacy or recency effects. The location of the red dot in the series was counterbalanced to appear in each of the squares an equal number of times. Each dot was followed by a 200 ms interstimulus interval, and each trial was followed by a click and the appearance of a blank grid of boxes. Participants responded by touching the order of the boxes in the same order in which the black dots appeared followed by the location of the red dot. The responses were followed by an intertrial interval of 1000 ms and an auditory click to signify a new trial. Figure 2 provides a visual schematic of the VS task. Each set size consists of 24 trials. Practice trials were administered prior to the experimental trials, and the participant was required to respond correctly to 80% of the practice trials to proceed.

Control (C) Conditions. The control condition is based on previously established protocols by Rapport and colleagues (Rapport et al., 2009). Baseline measurements of participants' activity level were collected while the participant used the Microsoft Paint program since this required minimal working memory demands as he/she drew or painted anything of his/her choice. Control condition activity measurements provide objective comparison data for possible changes in activity level while completing the experimental tasks (i.e. fatigue effects). Five consecutive minutes of baseline activity were collected prior to the participant completing the WM tasks (C1) and after completing the WM tasks (C2).

Procedure

Students who qualified for study participation (based on the Barkley Current Symptoms Scale – Self-Report symptom count cut-off score and/or affirmation of a previous ADHD diagnosis) were recruited via email. The email notification informed the participant that he/she was eligible for the study and provided a brief overview of the study's purpose and requirements. The student was provided with a code to access the study directly through an online research subject pool management system (SONA). From the SONA listing, the participant was able to access available session times and read additional information about the study. The participant was required to complete an online questionnaire session prior to his/her laboratory-based session. The online questionnaires were hosted by SurveyMonkey.com (a secure, data collection site) and contained additional measures (as part of a larger study) and background/psychosocial questionnaires (about social development, health history, employment history). The online portion required approximately 30 minutes to complete.

Each participant completed one laboratory-based session at the Center for Research of Attention and Behavior (CRAB). Upon arrival, the session administrator reviewed the informed consent with the participant and obtained consent to participate. The entire laboratory-based session lasted approximately 2.5 hours. The KBIT-2 was administered followed by a short break (three to five minutes) and administration of the K-SADS-PL. The clinical interview was video-recorded, which allowed the principal investigator and a second graduate student to review all participant profiles with the primary graduate student (session administrator) and determine group assignment.

Actigraphs were worn only during experimental tasks. Participants completed all the experimental tasks seated alone on a swivel chair approximately 0.70 m from a computer monitor in the testing room. Each participant completed two control conditions (C1 and C2), five phonological conditions (set sizes 3, 4, 5, 6, 7) and five visuospatial conditions (set sizes 3, 4, 5, 6, 7). Set size and WM modality (phonological or visuospatial) were counterbalanced to control for order and carryover effects, but the control conditions always occurred first (C1) and last (C2). All participants were offered breaks (two to three minutes) between tasks or taken as requested.

Upon completion of the lab-based session, participants were debriefed and provided with a copy of the previously signed informed consent. They were also asked to request participation from a parent/guardian to complete the collateral report form

(Barkley Childhood Symptoms Scale – Other Report Form). Documents for collateral informants (i.e., cover letter, informed consent, ratings scale) were reviewed with the participant prior to being mailed, and any questions related to the collateral ratings scale or study protocols were answered. Participants were informed during debriefing that credit for participation would be awarded upon receipt of completed collateral documents.

Dependent Variable

A total extremity score (TES) was calculated for each participant as a measure of overall movement. The TES is a summation of activity level (gathered from Action4 as described above) from each actigraph site (2 ankles, 1 non-dominant wrist) for each condition (twelve in total). Summed TES scores are preferred to other measures of central tendency and single extremity scores due to the ability of total scores to account for individual differences in localization of movement and to provide a more comprehensive sample of participants' overall activity level (Eaton et al., 1996).

CHAPTER IV

FINDINGS

Data Screening

Power Analyses. G*Power software (v. 3.1.2; Faul, Erdfelder, Lang, & Buchner, 2007) was used to determine the number of participants required to reliably detect differences with a repeated measures ANOVA. Power was set to 0.80 based on Cohen's recommendations and an effect size of 1.40. This effect size (ES) was chosen for comparability with the largest effect size reported in the most recent study examining executive functions and activity in adults (Lis et al., 2010), though this may result in an overestimate of the required sample size due to more sensitive measurement techniques (i.e., inclusion of informant ratings for classification, use of actigraphy for activity scores) employed in the current study. However, this ES was chosen rather than an ES from a previous child study that would likely result in an underestimate of the required sample size and potentially Type II error. Effect sizes are expected to be larger in studies with children, since the difference in activity level between individuals with ADHD and peers may become less pronounced in adulthood. Based on an ES of 1.40, alpha of 0.05, power equal to 0.80, 2 groups and 7 repetitions, 4 total participants would be needed to reliably detect within-subject differences and interaction effects, and 12 total participants would be needed to reliably detect between-subject differences. The current study included 28 total participants.

Outliers. Total extremity scores (TES) for each condition (C1, PH set sizes 3-7, VS set sizes 3-7, C2) were screened for univariate outliers (based on ≥3.29 *SD* above or below the group mean) that may skew group statistics during analyses (Tabachnick & Fidell, 2001). One TD participant's scores was identified as an outlier on PH set sizes 4, 5 and 6 and was replaced with activity level values equal to 3.29 *SD* for the group, following the recommendation of Tabachnick and Fidell (2001).

Data Imputation. Due to actigraph failure, activity data from three participants was missing from one actigraph location during at least one condition. Specifically, two participants were missing data from their non-dominant wrist during C2, and one participant was missing all data from his/her non-dominant wrist. The limited number of participants precluded listwise elimination of this data to ensure a sufficient number of participants were available for between-group comparisons. Based on recommendations to address missing data, a multiple imputation (MI) procedure was utilized (Sterne et al., 2009; Graham, 2009; Little, 1992). Activity levels from left ankle and right ankle actigraph locations during the same condition were used to predict the values for the missing data. A total run length of 4,000 iterations was used, with imputations after every 200th iteration to ensure that the imputations were independent. Twenty imputations were obtained in the current study.

Preliminary Analyses

The sample was comprised of 89% Caucasian, 7% African-American, and 4% Biracial participants. All self-report and collateral behavior rating scale scores were significantly higher for the ADHD group relative to the TD group (see Table 1). A Chi-Square test of association indicated no between-group differences in gender ($\chi^2(1) = .144$, $p = .705$) or racial composition ($\chi^2(2) = 3.04$, $p = .2193$). Independent samples t-tests indicated no group differences in age ($t(26) = -.971$, $p = .341$), intellectual functioning ($t(26) = -.484$, $p = .632$), or socioeconomic status ($t(25) = -.350$, $p = .730$); therefore, these variables were not included as covariates in any of the Tier I, II, III or IV analyses. Results are provided in Table 1.

Tier I (Composite Scores)

Tier I analyses examined differences in activity level between groups (ADHD, TD) and WM modalities (PH, VS). Composite scores for each modality were computed by averaging TES across set sizes. Using a 2x2 mixed-model ANOVA, a significant main effect for group ($F(1,26) = 4.61$, $p < .05$) was found, suggesting greater overall activity level in the ADHD group. There was no effect for WM modality ($p = .245$), and no interaction effect ($p = .580$). Results are depicted in Table 2. Theoretical models and previous literature supports the existence of performance and activity differences between WM modalities. Consequently, additional analyses were performed in Tier II to elucidate observed group differences and examine trends that may become significant with additional participants.

Tier II (Set Sizes)

Tier II analyses examined the effects of increased working memory demands on total activity level. A one-way MANOVA testing condition (C1, VS set sizes 3-7, PH set sizes 3-7, C2) by group (ADHD, TD) was significant for condition ($F(11,286) = 14.61$, $p < .001$) and group ($F(1,26) = 4.43$, $p = .045$). The ADHD group exhibited greater activity relative to the TD group, and all participants exhibited significantly greater activity during working memory conditions relative to baseline/control conditions. Two 2x7 mixed-model ANOVAs were used to examine between and within-group differences in total activity among conditions (5 set sizes, 2 baselines) for each modality (PH, VS).

For visuospatial conditions, there were significant main effects for group ($F(1,26) = 5.14$, $p = .032$) and condition ($F(6,156) = 27.75$, $p < .001$). The interaction between condition and group was also significant, $F(6,156) = 3.20$, $p = .005$. While all participants were more active during working memory conditions, participants in the ADHD group exhibited disproportionately larger changes in activity level across conditions, relative to the TD group. Post-hoc pairwise comparisons for all participants using Fisher's LSD indicated that activity level during all VS working memory conditions were significantly greater than during C1 (all $p < .001$) and C2 (all $p < .001$), but no differences were observed among VS working memory conditions (all $p > .05$). Post-hoc pairwise comparisons between groups using a one-way ANOVA indicated that the ADHD group was significantly more active during set sizes 3, 5, 6 and 7 (all $p < .05$), but no differences in activity were observed during C1, C2 or set size 4 (all $p > .05$). Post-hoc pairwise comparisons using Fisher's LSD were also completed to examine within-group differences in TES among conditions. Participants in the ADHD group exhibited significantly less activity during C1 compared to all other conditions (all $p < .026$) and C2 compared to all experimental conditions (all $p < .001$), but TES during all experimental conditions were not significantly different from one another (all $p > .05$). Participants in the TD group were also significantly less active during C1 compared to all other conditions (all $p < .020$) and C2 compared to all experimental conditions (all $p <$

.014), but no differences in TES were observed between any experimental conditions (all *p* > .05).

For phonological conditions, a significant main effect for condition was found (*F*(6, 156) = 22.68, *p* < .001), but there was no effect for group (*F*(1,26) = 3.09, *p* = .09). The interaction between condition and group was also nonsignificant, *F*(6,156) = 1.46, *p* = .197). Consistent with the VS modality, all participants exhibited a greater TES during phonological conditions than during control conditions. Post-hoc pairwise comparisons using Fisher's LSD indicated significantly greater activity levels during all PH working memory conditions compared to C1 (all *p* < .001) and C2 (all *p* < .001), but no differences among PH working memory conditions (all *p* > .05). Results are shown in Table 2 and Figure 3.

Tier III (Working Memory Components)

A latent variable analysis was used in this step to determine if differences in total activity level are associated with specific components of working memory. This approach is the best practice for determining the contribution of each WM component (CE, PH storage/rehearsal, VS storage/rehearsal) to activity level (Swanson & Kim, 2007; Rapport et al., 2009). Based on experimental and neurological findings, the PH and VS components are recognized as independent systems controlled by the domain-general central executive (Baddeley, 2003; Figure 4 provides a visual representation of the components examined in the latent variable approach). To separate the subsystem (PH, VS) storage/rehearsal processes from the CE, TES from the phonological task were regressed onto the visuospatial task TES at each set size. The residuals from this step represent the contribution of VS storage-rehearsal processes to activity at each set size. A similar procedure was then completed to obtain an estimate of the PH storage/rehearsal's contribution to motor activity. Specifically, the visuospatial TES was regressed onto the phonological TES at each set size, providing a residual score that represents the PH buffer/loop. Scores for each storage/rehearsal component were subsequently averaged across set sizes to provide a measure of the component's contribution to activity level. Finally, each regression provided a score that represents shared variability between the PH and VS subsystems. These scores were averaged across set sizes to provide a measure of the overall contribution of the domain-general central executive.

An independent samples t-test (ADHD, TD) was completed for each WM component (CE, PH storage/rehearsal, VS storage/rehearsal) to examine differences in activity level associated with each component of working memory. TES scores for the central executive were significantly greater in the ADHD group relative to the typically developing control group, *t*(26) = -2.153*,* *p* = .041*,* *d* = -.84. After controlling for the contribution of the central executive, between-group activity level differences were not significant for either the phonological, *t*(26) = .044, *p* = .965, or visuospatial storage/rehearsal components, *t*(26) = -1.797, *p* = .084.

CHAPTER V

CONCLUSION

The working memory model of ADHD (Rapport et al., 2001) proposes that working memory deficits serve as a core feature, or endophenotype, that underlie the ADHD phenotype, and motor activity serves as a compensatory mechanism that increases cortical arousal to meet working memory demands. The current study examined the functional relationship between activity level and working memory demands in adults with ADHD. An essential element of a comprehensive theoretical model of ADHD is the ability to account for observed changes in activity level into adulthood (Mick, Faraone, Biederman, & Spencer, 2004; Kessler et al., 2010) given evidence of persisting neurocognitive deficits (Boonstra, Oosterlaan, Sergeant, & Buitelaar, 2005; Hervey et al., 2004). Only one previous study has attempted to investigate activity level related to working memory demands in adults with ADHD (Lis et al., 2010), but the working memory task employed in the study may have been placed insufficient demands on the central executive, thereby concealing differences in activity level between adults with ADHD and typically developing adults. This is the first study to utilize actigraphy as an objective measure of activity level during working memory tasks and to include both phonological and visuospatial working memory tasks with variable working memory demands.

As a first step, the current study examined whether adults with ADHD continue to exhibit significantly more motor activity relative to typically developing peers. Previous studies have suggested hyperactive symptoms associated with ADHD tend to remediate after adolescence (Biederman et al., 2000; Hart, Lahey, Loeber, Applegate, & Frick, 1995; Hill & Schoener, 1996; Kessler et al., 2010; Larsson, Lichtenstein, & Larsson, 2006), while more recent studies suggest ADHD-related hyperactivity persists into adulthood (Halperin et al., 2008; Lis et al., 2010). Inconsistent findings in extant literature may be due to methodological differences in assessment procedures or task parameters. The current study improved upon previous methodological procedures by requiring collateral ratings rather than relying solely on self-report measures for group classification and by using objective activity measurement techniques (e.g., actigraphy). The inclusion of collateral ratings and objective activity measures is particularly important for accurate group classification and detection of ADHD-related activity, given literature that suggests adults with ADHD tend to underreport symptom presence and severity due to poor insight and difficulty with retrospective recall (Barkley, 1998; Smith et al., 2000; Barkley, 1997; Fischer, 1997; Wender, 1995; Kooij et al., 2008; McGough & Barkley, 2004). Collectively, the current results indicated that adults with ADHD were more active than typically developing controls, which provides support for the notion that excessive activity related to ADHD continues into adulthood.

Comparison of Working Memory and Control Conditions

The current study subsequently examined predictions from the working memory model of ADHD that suggest ADHD-related hyperactivity serves a compensatory role to increase cortical arousal needed to complete tasks with high working memory demands (Rapport et al., 2001). Collectively, all participants' activity increased during working memory conditions relative to control conditions, and adults with ADHD exhibited a disproportionate increase in activity level during working memory conditions, relative to adults in the typically developing group. Furthermore, while the ADHD group exhibited greater activity during most experimental conditions, no between-group differences in activity level were observed during control conditions. This suggests a functional relationship between ADHD-related activity and working memory demands in adults consistent with findings in children (Rapport et al., 2009) and refutes the notion that excessive activity is a ubiquitous feature of the disorder unrelated to task or situational demands (Porrino et al., 1983).

Comparison of Visuospatial and Phonological Conditions

A unique contribution of the current paper is the examination of activity level during discrete visuospatial and phonological working memory tasks. A recent study by Rapport and colleagues (2009) demonstrated that children with ADHD were more active than typically developing peers across both modalities, but all children exhibited greater levels of activity during phonological conditions compared to visuospatial conditions. A similar pattern was anticipated in adults; however, there were no between-group differences in activity level during the phonological working memory task, while adults with ADHD were disproportionately more active than typically developing adults during visuospatial working memory conditions. The discrepancy between the current study's findings with adults and previous findings with children may be related to several ontological and methodological variables. Phonological deficits observed in children with

ADHD (Rapport et al., 2008) may become less pronounced by adulthood as the phonological system has had time to catch-up in adults with the disorder, while the visuospatial system remains impaired. Adults may also be more flexible in their ability to use a variety of strategies for recalling stimuli (i.e., visual coding, verbal rehearsal), and the preferred strategy may be inadvertently influenced by task parameters.

Differences in the modality of stimuli presentation may also account for the current results contradicting findings with children. Specifically, Rapport et al. (2009) examined working memory with a phonological task that presented stimuli visually, whereas the current study utilized an auditory presentation of stimuli. The latter approach is expected to provide a more pure measure of the contribution of PH processes, as potential visuospatial demands associated with a visual presentation of numbers and letters, and the need for orthographic to phonological conversion of stimuli, were eliminated with the current methodology. Utilizing a visual presentation of phonological information may require additional attentional control (i.e., to inhibit the visual representation of the stimuli and to allocate resources to the articulatory rehearsal processes; Palmer, 2000) to complete the phonological recoding. Therefore, the current findings may represent a more accurate assessment of the motor activity associated with the phonological system than studies utilizing a visual presentation of stimuli, because the current methodology reduces demands on the central executive by eliminating the orthographic conversion process. In the previous child study (Rapport et al., 2009), greater motor activity associated with phonological conditions compared to visuospatial conditions may represent the contribution of the central executive during phonological conditions. This hypothesis is supported by examination of the independent component processes.

Comparison of Working Memory Components

Consistent with a priori hypotheses, the most substantial contribution to activity level was provided by the central executive, while the phonological and visuospatial storage/rehearsal subsystems did not significantly contribute to activity level after controlling for the contribution of the central executive. Current findings align with experimental studies of the functional relationship between working memory and activity level in children with ADHD that found increased motor activity was associated with greater demands on the central executive (Rapport et al., 2009; Alderson et al., 2011). Meta-analytic reviews of adult studies (Hervey et al., 2004; Boonstra et al., 2005) have found deficits in executive functions, but specific examination of the working memory components and associated impairments in adults has not been thoroughly conducted until the present study. Consequently, the current study is the first to demonstrate a functional relationship between executive impairments and adult motor activity.

Limitations and Future Directions

Findings from the current study provide important insight into the relationship between working memory and activity level in adults with ADHD, but a few limitations of the current study should be considered. The current sample was relatively small, but further data collection is planned. Additional participants may help to detect interaction effects as well as within-group and between-group differences that were not significant in current analyses. The composition of the current sample may also be considered a limitation and could be improved upon. For example, both the ADHD and typically developing groups included heterogeneous groups of males and females, and previous findings have demonstrated significant gender differences in working memory performance (Schweitzer et al., 2006). However, gender-related working memory differences do not appear to disproportionately affect ADHD or TD adults (Schweitzer et al., 2006), suggesting the current between-group findings does not reflect a gender bias. The current sample did not exclude any ADHD subtypes. Inclusion of the Predominantly Inattentive type may have resulted in an underestimate of adult activity due to fewer hyperactive/impulsive symptoms. Further, previous research has suggested that the subtypes differ in their underlying neurological characteristics and may represent distinctive disorders (Milich, Balentine, & Lynam, 2001; Lambek et al., 2010). Subtype differences in executive functioning, however, have not been consistently identified (Murphy et al., 2001). The current study reflects a preliminary examination of the association between motor activity and working memory in adults, and future studies that investigate the influence of gender and subtype on the relationship between working memory and activity level in adults with ADHD would augment the current findings.

General Conclusions

In summary, the current findings suggest that individuals with ADHD continue to exhibit significant levels of hyperactivity into adulthood. Current findings also lend support to the working memory model of ADHD (Rapport et al., 2001) which suggests that individuals with ADHD exhibit increased motor activity in response to increased demands on working memory, especially the central executive. Additional research is warranted to determine if inconsistent findings are associated with methodological differences (i.e., diagnostic procedures, task parameters) or are representative of differences in the underlying causes of ADHD symptomology. A thorough understanding of the underlying endophenotypes and lifetime course of ADHD symptoms would have broad theoretical and clinical implications. Identifying endophenotypes could greatly improve diagnostic accuracy if specific deficits could be readily assessed rather than relying on subjective reports of peripheral symptoms. A more thorough understanding of ADHD would also aid in developing appropriate treatment protocols that target specific neurological deficits and endophenotypes (i.e., working memory, behavioral inhibition) rather than peripheral symptoms (e.g., impulsivity, inattention). The current findings may ultimately inform behavioral strategies in home and school settings for individuals with ADHD, since interventions could be tailored to account for activity level differences and perhaps promote activity during challenging tasks (that tax working memory). The process of untangling deficits associated with ADHD-related symptoms is complicated by the lifelong nature of the disorder and requires that developmental perspectives be considered. Understanding that ADHD persists into adulthood and is associated with substantial lifelong difficulties increases the need to establish accurate diagnostic criteria, to develop appropriate interventions and to implement treatment strategies early in development.

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APPPENDIX

Overview of Attention Deficit/Hyperactivity Disorder

Attention-deficit/hyperactivity disorder (ADHD) is characterized by attention deficits, hyperactivity and impulsivity (Barnett et al., 2001), and occurs in three to eight percent of school-age children, according to current estimates (Barkley, 2006; Szatmari, 1992; Remschmidt, 2005). Extant epidemiological studies using factor analytic techniques differentiate three ADHD subtypes—Predominantly Inattentive, Predominantly Hyperactive-Impulsive, and Combined (Proctor & Prevatt, 2009). Individuals with the Predominantly Inattentive Type primarily exhibit difficulty organizing tasks, following instructions, listening when spoken to directly and paying close attention to details (e.g. making careless errors in schoolwork). Additional difficulties include being forgetful in daily activities and easily distracted, and losing items necessary for activities (e.g. school assignments, toys; American Psychiatric Association [APA], 2000; Bauermeister et al., 2005). The Inattentive subtype of ADHD (ADHD-I) accounts for 27% of children referred to outpatient clinics (Baeyens, Roeyers, & Walle, 2006). The Predominantly Hyperactive-Impulsive Type (ADHD-H) is marked by fidgeting or squirming, running or climbing excessively, difficulty engaging in quiet activities and interrupting others or blurting out responses. Affected individuals with the hyperactive-impulsive subtype tend to talk excessively, act before thinking, have difficulty waiting their turn, and exhibit excessive motor activity relative to same aged peers (APA, 2000; Bauermeister et al., 2005). Finally, the Combined Type (ADHD-C) is characterized by the presence of both inattention and hyperactivity-impulsivity symptoms (APA, 2000). Although studies in the general population have shown that ADHD-I is the most prevalent of the three subtypes in children, the ADHD-Combined Type (ADHD-C) is the most common subtype seen in outpatient clinics, constituting 55% of all referrals (Baeyens et al., 2006), and is associated with the most severe impairment (Gaub & Carlson, 1997; Graetz et al., 2001; Faraone et al., 1998; Hinshaw, 2002).

The prevalence of ADHD in North America is high relative to other psychiatric disorders but comparable to Europe and South America (Polanczyk et al., 2007; Faraone, Sergeant, Gillberg, & Biederman, 2003).Variability in prevalence rates worldwide appear related to variations in diagnostic criteria, the inclusion of impairment as a diagnostic requirement, and the source of the diagnostic information (i.e., comprehensive assessments or sole reliance on ratings scales; Polanczyk et al., 2007). ADHD is less prevalent in Hispanic children compared to African American and Caucasian children (Pastor & Reuben, 2008), and the disorder is more prevalent in boys across all three subtypes (Froehlich et al., 2007) with the closest male to female ratio (2:1) occurring in the Inattentive subtype (Lee, Oakland, Jackson, & Glutting, 2008). The latter finding may reflect differential symptom presentations across genders, such that girls affected with the disorder tend to exhibit fewer symptoms of hyperactivity and impulsivity compared to same-aged boys (Polanczyk & Rohde, 2007).

ADHD in Adolescents and Adults

ADHD was originally conceptualized as a disorder of childhood due to relatively low prevalence rates in adult relative to child studies (Fayyad et al., 2007), and a colloquial belief that children eventually outgrow the disorder and associated impairments (Resnick, 2005). More recent studies, however, provide strong evidence that ADHD persists into adulthood (Barkley et al., 2002; Kessler et al., 2006). The perceived remediation of the disorder in adulthood predominantly resulted from systematic methodological differences in earlier studies' diagnostic strategies when examining samples of children, adolescents, and adults. Whereas ratings from collateral informants (i.e. parents, teachers) were routinely solicited to identify the presence of ADHD in studies of children, diagnosis of ADHD in adulthood often relied on self-report ratings (McCann & Roy-Byrne, 2004; Rösler et al., 2006). The inclusion of symptom reports from multiple raters can greatly influence the rate of diagnosis and subtype differentiation (Rowland et al., 2008). Failure to meet diagnostic criteria in past studies of adults with ADHD may have resulted from subclinical self-reporting of symptoms, since previous research has shown that individuals with ADHD tend to underreport symptom presence and severity due to poor insight and difficulty with retrospective recall (Barkley, 1998; Smith et al., 2000; Barkley, 1997; Fischer, 1997; Wender, 1995; Kooij et al., 2008; McGough & Barkley, 2004). More recent studies of ADHD in adults have attempted to establish symptom presence prior to age seven (as designated in the DSM-IV-TR) via collateral report of childhood impairment across multiple settings (Miller, Newcorn, & Halperin, 2010). Other explanations for previous findings of symptom reduction in late adolescence and adulthood include the use of diagnostic criteria and measures that are designed for children and not adequately adapted to detect symptom manifestation in adulthood (Goodman, 2005; Searight, Burke, & Rottnek, 2000; McGough & Barkley, 2004; Faraone et al., 2006). Additionally, the increased presence of comorbid disorders with similar symptom presentation (e.g., psychomotor agitation occurring in depression, or restlessness observed in generalized anxiety disorder) may lead to diagnostic overshadowing of ADHD symptoms in an adult sample (Biederman et al., 1993).

ADHD is currently recognized as a lifelong disorder that continues into adolescence and adulthood, though the course of the disorder remains unclear due to challenges applying existing childhood diagnostic criteria (e.g., four versus six symptom cutoff) to adults (Kooij et al., 2005; Simon, Czobor, Bálint, Mészáros, & Bitter, 2009; Polanczyk et al., 2007). Estimates for ADHD persistence rates (from childhood to adulthood) range from 36.3 to 70% (Biederman, Mick, & Faraone, 2000; Polanczyk et al., 2007; Weisler & Goodman, 2008), suggesting upwards of 4 to 5% of the adult population meets criteria for ADHD (Kessler et al., 2006; Weisler & Goodman, 2008; Clarke, Heussler, & Kohn, 2005). Prevalence of ADHD subtypes in adults affected with the disorder show a pattern similar to childhood, with ADHD-C most prevalent (56%), followed by ADHD-I (37%) and ADHD-H (2%; Millstein et al., 1997).

ADHD is associated with numerous pejorative outcomes across the lifespan, including academic underachievement (e.g., lower GPA, SAT and ACT scores, and a higher rate of failure in college), poor peer relationships, family and romantic interpersonal difficulties (e.g., more marital problems and higher divorce rates), criminal activity, and low self-esteem (Barkley, Fischer, Smallish, & Fletcher, 2006; Sobanski et al., 2008; Slomkowski, Klein, & Mannuzza, 1995; Mannuzza, Klein, Bessler, Malloy, &

LaPadula, 1998). An estimated 87.5% of individuals with ADHD have a lifetime occurrence of a comorbid psychological disorder such as depression, substance use and eating disorders (Sobanski et al., 2008). The rates of comorbid substance abuse or dependence are reported to be as high as 35 percent (Kalbag & Levin, 2005) and significantly higher than rates observed in the general population (52% vs. 27%; Kalbag & Levin, 2005). Individuals with ADHD may be particularly vulnerable to suicidal behavior due to inadequate protective factors such as poor peer support (Barkley, 2006), underdeveloped social skills (Kats-Gold & Priel, 2009), and failure to benefit from traditional cognitive-based therapies for mood disturbances (Bramham et al., 2009). Additionally, hallmark symptoms associated with the disorder, such as impulsivity and difficulties with self-regulation (Wåhlstedt, Thorell, & Bohlin, 2008), may limit affected individuals' ability to withhold suicidal behaviors when ideations are present. Recent studies suggest a strong association between hyperactivity (Resch, Parzer, Brunner, & BELLA study group, 2008), ADHD-related impulsivity (Dougherty et al., 2004; Galéra, Bouvard, Encrenaz, Messiah, & Fombonne, 2008; Manor et al., 2010) and increased risk for suicide behaviors. More frequent impulsive or risk-taking behaviors characteristic of ADHD may also be associated with higher incidents of motor vehicle infractions and accidents (Barkley & Cox, 2007), physical altercations (Barkley, Fischer, Smallish, & Fletcher, 2004), traumatic brain injuries (Gerring et al., 1998), and court/legal involvement (Barkley et al., 2004). The annual societal cost of ADHD in children and adolescents (associated with parental work loss, health care, education services etc.) is estimated to range between $36 billion and $52.4 billion (Pelham, Foster, & Robb, 2007).

Historical Importance of Hyperactivity in ADHD

Hyperactivity has remained a constant in the clinical profile of children with ADHD, but the importance of the symptom has varied from the primary issue of clinical presentation to a more secondary feature of the disorder, and most recently to a symptom distinguishing subtypes of the overarching ADHD diagnosis. Depictions of hyperactivity and other characteristic ADHD symptoms have appeared in paintings and literature since 1670 (Kast & Altschuler, 2008). Hyperactivity was the first readily apparent feature of the disorder and took a prominent role in the first description of ADHD in Dr. Heinrich Hoffmann's 1845 children's story, "The Story of Fidgety Philip" (Thome & Jacobs, 2004). Though early clinical accounts of the disorder attributed the inability of some children to inhibit their behavior, and consequent hyperactivity, to a "defect of moral control" (Still, 1902, p. 1008), ADHD was soon conceptualized as a type of hyperkinesis or movement disorder akin to tics or compulsions. Hobhouse (1928) later explored the need to differentiate general "fidgetiness" from Sydenham's chorea, a disease characterized by abnormal motor movements (e.g. spastic limb movements or unnecessary reflex motions), and noted that the activity of restless, non-choreic children did not differ in topography from typically developing peers, but occurred with much greater frequency. Childers (1935) expanded Hobhouse's identification of hyperactivity as a significant clinical feature and was the first to identify commonly associated additional symptoms, such as excessive talking and sleep disturbance. In addition, Childers' research protocol ensured presentations of hyperactivity were clinically significant by requiring reports from multiple settings and observations of daily impairment (requirements now included in DSM diagnostic criteria).

Levin (1938) and Schneider (1945) also conceptualized hyperactivity as a behavioral disorder and examined potential physical explanations for the symptoms. Levin (1938) identified a subgroup of children who exhibited excessive motor activity without lesions to the frontal lobe or associated mental deficiency, though he speculated that overactivity was due to delayed maturation in the frontal region of the cerebral cortex. Alternatively, Schneider (1945) suggested that neurological, endocrine, visual, and speech abnormalities contributed to the general overactivity observed in hyperkinetic children.

Strauss and Lehtinen (1947) purported that restlessness and inattention were indicative of brain damage, even if undetectable, since the behavioral features were similar to symptoms in mental retardation and known brain injury. Ultimately, the moniker *minimal brain damage* (later, *minimal brain dysfunction, MBD*) was used to classify children with symptoms characteristic of ADHD (Wender, 1971) and believed to stem from localized lesions in the brain rather than gross neurological damage (Derby, 1972). Parents typically sought treatment for learning disabilities and viewed hyperactivity as a consequence of academic difficulties (Charlton, 1972).

This perspective changed in 1957 when Laufer and colleagues identified hyperactivity as an aberrant characteristic endogenous to the child and not due to traditionally accepted causes (i.e. encephalitis, severe head injury). The emphasis transitioned from a focus on etiological causes to observable behavior that typified the disorder. The diagnostic moniker shifted to *hyperkinetic impulse disorder* and was associated with hypermotility observable in infancy (particularly noticeable around five or six years old) and poor concentration, impulsivity and difficulty sustaining attention in the school setting. Birth complications, late developmental maturation, emotional disturbances and psychosocial concerns (e.g., mother-child relationship, family disruption) were speculated to result in dysfunction in the diencephalon region of the brain. However, children were presumed to outgrow the symptoms as this region developed through normal maturation processes (Laufer, Denhoff, & Solomons, 1957).

Changes in the diagnostic nomenclature to *hyperkinetic reaction of childhood* (from the DSM-II; APA, 1968) and *hyperactive child syndrome* (Chess, 1960) continued to emphasize the role of hyperactivity as the primary feature of the disorder with inattention considered a secondary problem. The hyperkinesis monikers were replaced in the 1970s after influential work by Douglas (1972; Douglas & Peters, 1979) and Campbell (Campbell, Douglas, & Morgenstern, 1971) that identified deficits of attention and impulse control as the principal feature associated with behavior problems in children. The diagnostic moniker *attention deficit disorder* (ADD) was adopted with the publication of the DSM-III (APA, 1980) to emphasize attention and inhibition difficulties as the core deficits of the disorder, and hyperactivity as a secondary feature (Douglas, 1972). Children that only exhibited deficits of attention and impulsivity were diagnosed as ADD without hyperactivity (ADD/WO), while children who also exhibited developmentally inappropriate excessive motor activity were diagnosed with ADDH (ADD with hyperactivity). The distinction in diagnostic nomenclature reflected the belief that hyperactivity was the distinguishing feature between the symptom presentation of two distinct disorders (Lahey, Schaughency, Hynd, Carlson, & Nieves, 1987).

As with previous diagnoses of MBD and hyperkinesis, the clinical utility of the DSM-III was limited due to poorly specified diagnostic criteria required for diagnosis

(Carey & McDevitt, 1980). The DSM-III-R (APA, 1987) revised the diagnostic moniker to *attention-deficit/hyperactivity disorder* and specified three domains (inattention, impulsivity, hyperactivity). Hyperactivity regained status as a central feature of the disorder with diagnostic criteria that required the presence of eight symptoms across two domains. Factor analysis of teacher ratings revealed two dimensions – hyperactivity-impulsivity and inattention – consistent with the hypothesized DSM-III-R domains (Healey et al., 1993). The publication of the DSM-IV (APA, 1994) further promulgated the delineation of symptom presentation by creating subtype designators – predominantly inattentive, predominantly hyperactive-impulsive, combined type – based on symptom identification from two clustered lists. Factor analytic techniques of parent ratings again found two distinct dimensions (hyperactivity-impulsivity and inattention) that supported the use of subtype distinctions (DuPaul et al., 1998). Hyperactivity has remained a central feature of the disorder, and extant conceptual models of ADHD provide hypotheses to explicate the relationship between hyperactivity, impulsivity and attention problems.

Assessment of ADHD-Related Hyperactivity

Although the current literature is replete with studies examining activity level in children, adolescents, and adults with ADHD, variation in measurement techniques have produced conflicting findings. Parent and teacher ratings on standardized ratings scales, such as the Conners Parent/Teacher Rating Scales (Conners, Sitarenios, Parker, & Epstein, 1998), Child Behavior Checklist and Teacher Report Form (Achenbach & Rescorla, 2001), and Behavioral Assessment System for Children (Reynolds & Kamphaus, 2004), are commonly used to identify children who display behavior problems, including excessive motor activity. To date, study findings have been equivocal. Only a minority of studies have found that ratings scales are able to assess activity level as well as objective measures (e.g., actigraphs). For example, a previous study demonstrated that parent and teacher ratings of hyperactivity were moderately correlated with actigraph measurements (.29 and .32, respectively) in a nonclinical sample of children (Reichenbach, Halperin, Sharma, & Newcorn, 1992), while a second study demonstrated moderate correlations between parent and teacher ratings and objectively measured (actigraphs) activity (Wood, Rijsdijk, Saudino, Asheron, & Kuntsi, 2008). A recent review found that parents report children with ADHD are more restless during sleep relative to typically developing children, despite objective measurements of nighttime activity that fail to demonstrate differences in sleep activity (Cohen-Zion & Ancoli-Israel, 2004). A more recent study measured activity with actigraphs over a period of one week (24 hours per day for 7 days) and found that the ADHD-C group was not significantly more active than controls at home or school, despite parent and teacher ratings that suggested otherwise (Licht & Tryon, 2009).

The discrepant findings between ratings scales and objective measures across studies may be due to methodological variables such as heterogeneity in ratings scales (i.e., broadband versus narrowband measures), time of day that data is collected (i.e., nighttime versus daytime) or setting variations (i.e., lab-based sessions versus unstructured play times). In addition, ratings scales may be unable to differentiate ADHD subtypes due to overlap implied in some criteria (i.e., an impulsive action frequently coincides with hyperactivity; Rapport et al., 2008). Finally, ratings scales are subject to self-reporting and observer bias and may not adequately differentiate symptoms of ADHD from other disorders with similar symptom presentations that may reflect physiological arousal (e.g., restlessness, feeling “on-the-go”; Tannock, 2000; Jarrett & Ollendick, 2008).

The use of pedometers (Plomin & Foch, 1981), stabilimetric cushions (Conners & Kronsberg, 1985), grid/quadrant crossings (Rapoport, Abramson, Alexander, & Lott, 1971), infrared motion analysis (e.g., OPTAx test; Teicher et al., 1996), and actigraphs (Porrino et al., 1983) have been employed to provide a more objective measure of activity, relative to subjective ratings provided by parents, teachers, and other observers. Grid crossings (recording movements into subdivided grid sections of the larger observational space) provide detailed information about behavior but are often obtainable only in a structured environment (often a classroom or laboratory testing session). In addition, methodological difficulties may include between-study variability in behavioral definitions, disagreement between raters and observer drift, and high investment of time to observe, code, and summarize data (Mason & Redeker, 1993; Rapport et al., 2006). Pedometers and infrared motion analysis improve upon some of these concerns by eliminating the element of human error associated with observation-based activity measurement. Pedometers assess the amount of gross/total activity, while infrared motion analysis detects a more precise range of movements (Tryon, Pinto, & Morrison, 1991; Teicher et al., 1996). This method, however, requires a stationary sensor that records infrared motion, thus limiting the types and amount of movement that can be recorded (e.g., participant is outside range of sensor detection). In addition, variability in placement of the infrared sensors (head, shoulder, arm) may influence study findings (Teicher et al., 1996; Bell, 1968).

Actigraphs (and the earlier model actometers) measure acceleration, or finite changes in movement, more frequently and more accurately than previous methods without restrictions on settings or time of day (Patterson et al., 1993). For example, MicroMini-Motionlogger actigraphs resemble non-intrusive watches and sample the participants' activity 16 times per second. Actigraphs require supplemental behavioral coding, however, to determine the specific actions that resulted in increased or decreased activity levels. Difficulties associated with actigraphs center on mechanical malfunction and differences in placement location (ranging from waist/trunk to wrist to head to ankles) by study, though most utilize multiple sites to control for variability in motor activity by extremity (Paavonen, Fjällberg, Steenari, & Aronen, 2002; Tryon, 1991).

Early actigraph studies of adults with ADHD initially examined changes in activity from day to night and medication effectiveness (i.e., activity level with or without medication), and study findings yielded inconsistent results. Boonstra and colleagues (2007) found that adults with ADHD were only more active during the day and not during the night over the course of seven days, relative to adults without the disorder (Middelkoop, van Gils, & Kooij, 1997). Actigraphs have also been used to compare activity level in antisocial violent offenders with a history of ADHD, healthy controls, and individuals with akathisia (a side effect of antipsychotic drugs characterized by restlessness, difficulty remaining seated and feeling an urge to move; Tuisku et al., 2003). The ADHD group exhibited significantly more activity relative to healthy controls but similar to the akathisia patients. A more recent study by Halperin and colleagues (2008) utilized actigraphs placed on the non-dominant ankle and waist and found that adults diagnosed with ADHD during childhood exhibit higher levels of activity than non-affected adults, irrespective of whether they continue to meet diagnostic criteria for ADHD (Halperin et al., 2008). Collectively, these findings suggest that actigraphs are an appropriate tool for the objective measurement of activity level in adults.

Hyperactivity in Theoretical Models of ADHD

Extant literature has attempted to examine the importance of hyperactivity in differentiating ADHD subtypes and accurately diagnosing ADHD, yet models of ADHD vary in the extent with which the presence and role of hyperactivity is described.

Cognitive Energetic Model (CEM)

Sergeant and colleagues' (1999) cognitive-energetic model (CEM) of ADHD suggests that an individual's efficiency of information processing is influenced by the top-down and bottom-up interactions of three levels—computational mechanisms of attention (encoding, search, decision, motor organization), state factors (energetic pools) and management/executive functions (planning, monitoring, detecting and correcting errors; Sergeant, 2005). Three energetic pools – effort (energy to meet task demands), arousal (timely processing and response influenced by intensity and novelty of stimuli), and activation (physiological preparedness to initiate a response) – comprise the second level of the CEM. Deficits are believed to occur at each level in ADHD. The CEM does not offer any testable hypotheses about the role of hyperactivity in ADHD; however, the theoretical role of the energetic pools may be relevant to the current study. A measureable *event rate* (speed of stimuli presentation) is tied to an individual's alertness or physiological readiness to respond (activation pool) and alters the energetic state when adjusted. Previous research identified poorer performance by children with ADHD when event rates were slow (compared to fast trials), perhaps due to underarousal or an inability to adjust their energetic state according to task demands (Sergeant et al., 1999; Van der Meere, Vreeling, & Sergeant, 1992). Children with ADHD are less accurate with slow event rates since responses (and thus motor movements) are required less frequently, and fast event rates tend to elicit task performance similar to individuals without ADHD (Van der Meere et al., 1992). This explanation of energetic state variability does not account for observed hyperactivity but suggests that an ADHD individual's task performance is influenced by their ability to adapt their motor movement (and resulting energetic state).

Inhibition Models – Dual Pathway Model & Behavioral Inhibition Model

Behavioral inhibition is a central component to two prominent theoretical models of ADHD. The dual pathway model (Sonuga-Barke, 2002) and the behavioral inhibition model (Barkley, 1997) emphasize deficiencies in inhibitory control as a core feature of ADHD that results in cognitive (e.g., difficulty engaging tasks, distractibility) and behavioral (e.g., impulsivity, hyperactivity) dysregulation. The dual pathway model (Sonuga-Barke, 2002) suggests that thought/behavior regulation and motivational style are disordered in ADHD and each contribute to a distinct set of symptoms. In the motivational style pathway, biologically-based reward circuits (in the ventral-striatal network) are altered due to genetic (i.e., meso-limbic dopamine levels) and environmental factors (i.e., inflexible, demanding parenting, and unrealistically high self-expectations) thus influencing task engagement as children with ADHD discount the value of future events. Delay aversion and behavioral impulsiveness develop over time as the individual fails to respond appropriately to situational demands related to waiting (e.g. lunch line at school, taking turns in a game, backup in traffic), and these settings become aversive (Sonuga-Barke, 2002). Impulsiveness is likely to occur in settings in which the child or adult has immediately available choices, whereas excessive activity and inattention are likely to occur in settings in which the child perceives no alternative to a delay and consequently engages in avoidance or escape behavior.

Both the behavioral inhibition (Barkley, 1997) and dual pathway (Sonuga-Barke, 2002) models emphasize the dysregulation of inhibitory control as upstream of other executive functions (i.e. planning, behavioral monitoring, working memory) and secondary behavioral effects (i.e. impulsivity, overactivity). However, there is a significant distinction – the dual pathway model does not purport a direct pathway between executive functions and ADHD symptoms. The behavioral inhibition model identifies impairments in three specific inhibition processes: prepotent response inhibition, discontinuation of an ongoing response, and interference control. These processes are hypothesized to impair functioning in more complex executive functions such as working memory, self regulation of affect-motivation-arousal, internalization of speech, and reconstitution (Barkley, 1997). Individuals rely on these four executive functions to use internally represented information to provide control, timing, flexibility and syntax (i.e., instructions based on previous behaviors) for motor actions in order to inhibit task-irrelevant behaviors as well as coordinate complex, novel goal-directed behaviors. The execution of motor sequences is disrupted due to deficits in the reconstitution process, which is responsible for the generation of behavioral instructions. Collectively, excessive motor activity (or inadequate inhibition of task-irrelevant movement) is viewed as a ubiquitous behavior that results from a behavioral inhibition deficit preventing the executive functions from controlling task-irrelevant behaviors (Barkley, 1997).

Sonuga-Barke (2002) suggests that behavioral symptoms (e.g. hyperactivity) are the result of behavioral dysregulation (i.e. inhibitory control dysfunction) and altered reward mechanisms in a feedback loop that ultimately limits the individual's ability to develop higher order skills (i.e. executive functions), but this conclusion is primarily descriptive and does not offer predictions about continuity of deficits into adulthood. This model predicts that overactivity may be remediated by a change in context or by restructuring tasks (to increase inhibitory control through task engagement).

Neurodevelopmental Model

The neurodevelopmental model of ADHD (also called the prefrontal recovery hypothesis; Halperin & Schulz, 2006) describes the developmental course of the prefrontal cortex in relation to executive functions and ADHD symptoms. Halperin and Schulz (2006) propose that differences in onset of symptom presentation in individuals with ADHD are related to differences in the development of the prefrontal cortex. This is based on findings that ADHD does not result from brain-damage to this region in children, but ADHD-like symptoms occur in instances of damage to the well-developed prefrontal cortex in adults. Deficits observed in children with ADHD may be related to functioning in the prefrontal cortex, but environmental influences and developmental progression allow for neural reorganization and functional compensation (of structural deficits) that remediate observed deficits in the prefrontal cortex over time (Halperin & Schulz, 2006). Developmental maturity of the prefrontal cortex and associated executive functions appear to correspond with the reduction of symptoms observed in ADHD children as they transition to late childhood and adolescence. Top-down compensatory mechanisms (i.e. self-regulation processes) may develop in the prefrontal cortex to compensate for cognitive deficits elsewhere (Halperin & Schulz, 2006).

This hypothetical perspective helps explain the association between executive function deficits and severity of ADHD symptoms proposed by the behavioral inhibition model, as well as the motivational deficits (when children with ADHD are required to use more effortful processes in situations that others process automatically) described by the dual pathway model (Halperin & Schulz, 2006). Localization of the underlying cause of ADHD remains unknown, but Halperin and Schulz (2006) suggest that the reduction in symptoms seen across the lifespan is directly related to the prefrontal cortex. Specific hypotheses related to activity reviewed by Halperin and Schulz (2006) suggest that anomalies in the caudate nucleus within the basal ganglia are related to hyperactivity in children with ADHD. The basal ganglia serves as the center through which intentional motor behaviors are disinhibited and competing motor signals are inhibited (Mink, 1996). Basal ganglia dysfunction is hypothesized to play a role in ADHD based on identification of structural and functional abnormalities (i.e., reduced caudate volume, increased dopamine transporter density; Castellanos, Lee, & Sharp, 2002). The subsequent development of this caudate region seems to be associated with the reduction of excessive activity reported in adolescence but cannot account for the persistence of some symptoms into adulthood.

Functional Working Memory Model of ADHD

Brief Overview

The functional working memory model of ADHD hypothesizes that working memory deficits, particularly the domain general central executive, serve as a core feature (Rapport et al., 2001; Rapport et al., 2008) or endophenotype (Castellanos & Tannock, 2002) that is responsible for cognitive (inattention), behavioral (hyperactivity/ impulsivity), and psychosocial problems (e.g., academic underachievement, poor peer relationships) characteristic of the ADHD phenotype (Rapport et al., 2001). That is, the model suggests that working memory deficits are upstream of behavioral inhibition, self-regulation, delay aversion and DSM-IV defined core deficits (i.e., impulsivity, inattention, hyperactivity). The functional working memory model is based on Baddeley and Hitch's (1974) working memory model that describes a three-component information processing system that includes independent visuospatial and phonological processing and rehearsal/storage systems, as well as a domain general central executive attentional controller.

Baddeley’s Working Memory Model

Working memory involves the temporary storage and active manipulation of internal information and is comprised of a domain-general central executive and two subservient subsystems—the phonological loop (associated with storage and rehearsal of verbal information) and the visuospatial sketchpad (associated with storage and rehearsal of visual and spatial information; Baddeley, 2007).

The phonological (PH) loop is comprised of a phonological buffer and an articulatory loop. The phonological buffer provides temporary storage for phonological information (lasting a few second before beginning to fade), while retention of information in the buffer is extended by the articulatory rehearsal process (re-articulation similar to subvocal speech; Baddeley, 2003). Empirical evidence for the PH loop is provided by investigation of two robust phenomena--the phonological similarity effect and the word length effect (Logie, Della Sala, Laiacona, Chalmers, & Wynn, 1996). The phonological similarity effect suggests that similar sounding stimuli (e.g., T-P, boat-coat) are more difficult to recall in comparison to dissimilar sounding stimuli (e.g., K-L, cookie-dog; Conrad & Hull, 1964) due to interference created by similar sounding stimuli during the articulatory rehearsal process (Baddeley, 1966). The word length effect suggests an individual's ability to recall words immediately after presentation declines as the length of the words increase because shorter words are able to be rehearsed more frequently than longer words, thereby increasing exposure to the words and facilitating recall (Baddeley, Thomson, & Buchanan, 1975). The presence of the articulatory rehearsal process is further supported by the extinction of the word length effect (also referred to as irrelevant sound effects) in dual task protocols. When individuals are required to repeat sounds or small words (e.g., la, the) following a list of target words, they are less accurate in recalling the target words because the subvocal rehearsal process is disrupted (Murray, 1968). Performance is not affected by phonological similarity between the stimuli words or between the stimuli words and the irrelevant sounds (Salamé & Baddeley, 1986; Jones & Macken, 1995; Larsen, Baddeley & Andrade, 2000).

The visuospatial (VS) sketchpad processes visual and spatial information analogous to the processing of verbal information by the phonological loop. The visuospatial sketchpad is responsible for the temporary storage and manipulation of visuospatial information received from the environment or retrieved from long-term memory (Baddeley, 2007). Neuropsychological studies have provided evidence for visuospatial memory (Suchan, 2008) as well as a distinction between the visual and spatial memory components (Baddeley, 2007). For example, findings from a previous study showed that visual interference reduces visual performance but not spatial performance, thus providing evidence for two separate components (Della Sala, Gray, Baddeley, Allamano, & Wilson, 1999). Similarly, a study in visuospatial imagery found that individuals performed more poorly on a memory task when they were required to simultaneously complete a visuospatial task (i.e., tracking a moving light stimulus; Logie, 1986). This finding provides evidence that the visuospatial sketchpad is a limited capacity system for the temporary storage of visuospatial information, similar to the phonological buffer's storage of text-based information.

The central executive (CE) was originally viewed as a "pool of general processing capacity" (Baddeley, 2003, p. 835) but was revised to include the supervisory activating system (SAS; Norman & Shallice, 1986). The SAS provides supervisory, attentional control when automatic processes, driven by cues from the environment, are insufficient. The particular level of control is determined by task difficulty with automatic actions operating at a lower, habituated level and novel responses requiring processing at a higher, attended level (Baddeley, 1996). Conceptualization of the CE has more recently transitioned from a simple controller of the two subsystems (PH loop and VS sketchpad) to a more active component in the working memory process (Baddeley, 2007). Currently, the CE is hypothesized as a domain general system involved in focusing, dividing and shifting attention. The CE also coordinates storage and rehearsal sub-components of the phonological loop and visuospatial sketchpad (Baddeley, 1996; Bourke, Duncan, & Nimmo-Smith, 1996). A visual schematic of Baddeley's working memory model is displayed in Figure 5.

Neuropsychological research has provided strong evidence supporting Baddeley's working memory model. Neuroimaging studies suggest the left temporoparietal region is associated with the phonological loop, whereas the visuospatial sketchpad has been primarily associated with the right hemisphere (Smith & Jonides, 1997; Smith, Jonides, & Koeppe, 1996; Paulesu, Frith, & Frackowiak, 1993; Suchan, 2008). The visual-object component of the visuospatial sketchpad appears to be localized within the occipital lobe, while the spatial component involves the inferior parietal lobe (Smith & Jonides, 1997; Baddeley, 2003). Neuroimaging studies of overall executive functioning, particularly involving integration and coordination of both working memory components (PH and VS), suggest a strong association between these functions and the frontal lobes (Smith & Jonides, 1997; Wager & Smith, 2003). Finally, extensive literature supports the independent functioning of the VS and PH working memory components and their associated neural structures (Alloway, Gathercole, & Pickering, 2006; Fassbender & Schweitzer, 2006; Baddeley, 2003; Vallar & Papagno, 2002; Smith & Jonides, 1997).

<u>Working Memory Deficits, Inattention, and Hyperactivity</u>

A previous review conducted by Rapport and colleagues (2000) examined a broad range of executive function measures to determine their relative usefulness in accurately identifying children with ADHD. Measures that appeared to place greater demands on the working memory system, and the phonological loop in particular, were the most effective at reliably distinguishing children with ADHD from typically developing controls

(Rapport et al., 2000). This finding ultimately led to the development of the functional working memory model of ADHD.

While earlier theories (and the DSM-IV criteria) identify attention and hyperactivity-impulsivity as core features of the disorder, the functional working memory model of ADHD suggests these features occur secondary to an underlying core deficit in working memory (Rapport et al., 2001). A visual representation of the working memory model of ADHD is provided in Figure 6. According to the model, biological influences (e.g., genetics, prenatal factors) contribute to alterations of neurobiological systems (e.g., dopamine dysregulation, cortical underarousal) that result in deficient working memory processes. Working memory plays a vital role in an individual's ability to maintain representations of stimuli, to match the representations to memory, and to access and initiate behavioral responses appropriate to task demands.

The model hypothesizes that ADHD-related attention deficits result from stimulation seeking or attempts to increase the rate of stimuli input, due to an inability to adequately maintain representations of environmental stimuli in working memory. Redirection of attention may also occur when task demands become too high and attention is shifted away from aversive (or demanding) stimuli that cannot be adequately processed due to rapid memory decay. The topography of these attention shifts may be interpreted as hyperactive or impulsive behavior, while excessive movement may also serve as a form of escape from tasks with high working memory demands. The working memory model of ADHD is particularly unique in its ability to provide testable predictions regarding the cause and function of hyperactivity. Increased motor activity observed in children with ADHD serves as a compensatory mechanism to increase cortical arousal required to complete tasks that place high demands on central executive functioning.

Extant studies of neurological correlates provide strong evidence for executive function deficits (e.g., working memory) in ADHD. For example, MRI studies reveal that individuals with ADHD have less cortical gray matter and prefrontal cortex volume, as well as decreased activation in the anterior cingulate (often involved in cognitive tasks), relative to non-affected individuals (Castellanos et al., 2002; Bush, Valera, & Seidman, 2005; Seidman, Valera, & Makris, 2006; Bush, Frazier, & Rauch, 1999). In addition, Valera and colleagues (Valera, Faraone, Biederman, Poldrack, & Seidman, 2005) found decreased activity in the cerebellar and occipital regions in adults with ADHD compared to controls during a working memory task, and dopaminergic dysfunction in the medial and left lateral prefrontal cortex has already been shown to mediate the presence of adult ADHD symptoms (Ernst, Zametkin, Matochik, Jons, & Cohen, 1998). Increased theta wave activity, decreased blood flow to the frontal lobe, and dopamine deficiency in individuals with ADHD is associated with cortical underarousal and subsequent deficiencies in working memory (Castellanos & Tannock, 2002; Loo & Barkley, 2005).

Children with ADHD are impaired in all three components of working memory, with the largest deficits found in the central executive system, followed by visuospatial storage/rehearsal and then phonological storage/rehearsal subsystems (Martinussen et al., 2005; Rapport et al., 2008; Karatekin, 2004). Three previous meta-analytic reviews found children with ADHD performed significantly worse on working memory tasks relative to typically developing children, with strong between-group effect sizes ranging between .43 and 1.06 (Martinussen et al., 2005; Willcutt et al., 2005; Pennington & Ozonoff, 1996). The first review that examined working memory in children with ADHD found they performed similarly to typically developing children on verbal and visuospatial memory tasks, with only one-fifth of studies reporting significant differences in these areas (Pennington & Ozonoff, 1996). A meta-analytic review conducted by Willcutt and colleagues (2005) found significant effect sizes on tasks of spatial (ES = .75) and verbal (ES = .59) working memory in children and adolescents with ADHD in comparison to typically developing controls. A second meta-analytic review examined between-group (ADHD, TD) differences in specific working memory components by sorting tasks into verbal storage, verbal central executive (CE), spatial storage and spatial central executive categories (Martinussen et al., 2005). When compared to controls, children with ADHD were found to perform significantly worse across all domains, with the greatest impairment on spatial storage tasks, and particularly the spatial CE tasks.

Experimental studies published since the most recent meta-analytic review have continued to provide strong evidence for working memory as a core feature of the disorder, and consequently support the working memory model of ADHD. For example, Rapport and colleagues (2008) found that children with ADHD performed significantly worse across all working memory domains (i.e., central executive, visuospatial and phonological) relative to typically developing controls, with between-group effect sizes that were considerably larger (i.e., Hedges’ g ranging from 0.6 to 2.8) than those typically found in studies utilizing other executive function tasks (Willcutt et al., 2005). More recent empirical studies have demonstrated that working memory can account for the core features of ADHD currently defined in the DSM-IV-TR—attention deficits, impulsivity, and hyperactivity. For example, a recent study demonstrated that ADHD-related attention deficits are directly related to increased demands on the central executive component of the working memory system (Kofler, Rapport, Bolden, Sarver, & Raiker, 2010). A second study found that working memory, particularly the visuospatial system and central executive, fully mediated the relationship between ADHD deficits and behavioral inhibition (Alderson, Rapport, Hudec, Sarver, & Kofler, 2010). A series of recent studies have examined the role of working memory on activity level in boys with ADHD and typically developing controls. Collectively, these studies found that increased ADHD-related motor activity was functionally related to increased demands on the working memory system, and particularly the central executive (Rapport et al., 2009; Alderson et al., 2011).

Working Memory in Adults with ADHD

Extant studies of adults with ADHD provide evidence of impairment in interference control (Corbett & Stanczak, 1999), attention, response inhibition and visuospatial working memory (Murphy, Barkley, & Bush, 2001; Barkley, Murphy, & Kwasnik, 1996), while findings from three previous meta-analytic reviews suggest performance deficits in executive functions (e.g., working memory, set-shifting, verbal fluency, sustained attention) continue into adulthood (Hervey et al., 2004; Boonstra et al., 2005; Schoechlin & Engel, 2005). More recent experimental studies of adults with ADHD have revealed deficits on phonological (Schweitzer et al., 2006; Dige & Wik, 2005; Marchetta, Hurks, Krabbendam, & Jolles, 2008) and spatial (Clark et al., 2007) working memory tasks. These impairments mirrored performance profiles of individuals with frontal cortex lesions suggesting that similar neurological abnormalities in this region contribute to ADHD symptoms (Clark et al., 2007) but may be improved with stimulant medication (Aron, Dowson, Sahakian, & Robbins, 2003). Finally, consistent with the working memory model of ADHD, executive function deficits in adults with ADHD are associated with lower academic achievement (Biederman, Faraone, Monuteaux, Bober, & Cadogen, 2005) and inattention-disorganization (Nigg et al., 2005), and result in poorer adaptive functioning relative to non-affected peers (Stavro, Ettenhofer, & Nigg, 2007).

Though working memory deficits (Hervey et al., 2004) and increased activity level (Boonstra et al., 2007; Halperin et al., 2008) have been found in adults with ADHD, only one study to date has examined the relationship between these features. A recent study conducted by Lis and colleagues (2010) examined levels of motor activity during a working memory task in adults with ADHD and healthy controls. Participants were administered a visual n-back task that required them to judge whether a stimulus matched the immediately preceding stimulus in a sequence, based on color (blue, red) and shape (circle, square). Participants responded only if both features of the stimuli matched, which occurred in 25% of trials. Collectively, participants with ADHD made significantly more omission errors (i.e., missing target stimuli) relative to participants in the control group, while between-group differences in commission errors (i.e., reactions to non-targets) were not significant. Furthermore, impaired task performance was significantly associated with an increase in objectively measured activity level in adults with ADHD compared to controls.

Lis and colleagues' conclusion that increased motor activity is associated with cognitive impairments in adults with ADHD, however, should be tempered given there are several potential limitations that warrant consideration. The diagnostic/grouping procedure relied solely on self-report measures (Adult Self-Report Scale and Wender-Utah-Rating-Scale-Short Version) for assessment of childhood and current symptoms. The use of collateral informants is typically preferred, since adults with ADHD tend to inaccurately report symptoms and have difficulty with retrospective recall (McGough & Barkley, 2004; Smith et al., 2000). The inclusion of a semi-structured interview to assess present symptomology is helpful but could be improved by including a second diagnostician (to provide interrater reliability) and utilizing a semi-structured interview that assesses a broader range of symptomology across the lifespan (to differentiate diagnosis of another disorder with similar symptom presentation).

In addition, the use of a 1-back task provides limited information about the nature of the working memory deficits (e.g., phonological or visuospatial comparison) since the participant is only required to retain the most recently presented item for comparison to the test stimulus. Collectively, the task is essentially a 2-choice recognition task that does not require extensive manipulation or recall of the stimuli and may not engage the same processes that are typically assessed with more complex working memory tasks (Jaeggi, Buschkuehl, Perrig, & Meier, 2010). Furthermore, activity level was assessed with an infrared motion analysis detector that calculated the divergence from a center point at regular intervals. This measurement technique may not provide the best estimate of activity level, since head movement is not necessarily indicative of excessive motor activity in extremities overall (e.g., a participant may be sitting without movement but have lowered his head which is registered as extreme activity though he is actually motionless; Rapport et al., 2006; Teicher et al., 1996). Finally, Lis and colleagues' failure to include a control condition limits conclusions regarding the direct relationship between increased working memory load and activity level.

Table 1. Sample and demographic variables

	ADHD (*n*=14)	TD (*n*=14)		
	M (SD)	*M (SD)*	χ^2	*t*
Gender Ratio (Male:Female)	7:7	8:6	0.144	
Racial Composition			3.04	
Age	19.93 (2.20)	19.29 (1.14)		-0.971
IQ Composite (K-BIT-2)	102.79 (10.59)	100.64 (12.72)		-0.484
Socioeconomic Status	50.62 (12.63)	49.32 (5.51)		-0.350
Barkley-Current-Self	32.93 (9.6)	14.00 (11.56)		-4.71***
Barkley-Childhood-Other	32.71 (9.45)	5.71 (5.89)		-9.07***

Note. ADHD = Attention-Deficit/Hyperactivity Disorder; K-BIT-2 = Kaufman Brief Intelligence Test-2; M = Mean; SD = Standard Deviation; TD = Typically-Developing

***p < .001

Table 2. Composite and set size comparisons of total extremity scores

	ADHD (*n*=14)	TD (*n*=14)		
	M (SD)	*M (SD)*	*F*	*Post-hoc LSD*
Group X Modality			0.32	
PH Composite	17952 (11209)	12100 (5181)	—	
VS Composite	17388 (10015)	10530 (3872)	—	
Group X PH Set Size			1.46	
Control 1	6507 (4390)	4170 (2701)	—	
Control 2	8248 (4815)	6751 (4658)	—	
PH Set Size 3	18365 (11150)	12232 (6176)	—	
PH Set Size 4	18994 (13683)	12432 (6200)	—	
PH Set Size 5	17744 (11851)	10945 (5619)	—	
PH Set Size 6	17963 (13677)	12025 (5260)	—	
PH Set Size 7	16694 (8689)	12866 (7498)	—	
Group X VS Set Size			3.20**	
Control 1	6507 (4390)	4170 (2701)	2.88	
Control 2	8248 (4815)	6751 (4658)	0.70	
VS Set Size 3	18843 (8794)	10761 (4007)	9.79**	ADHD > TD
VS Set Size 4	16761 (11157)	11318 (6548)	2.48	
VS Set Size 5	17756 (11364)	10197 (4760)	5.27*	ADHD > TD
VS Set Size 6	17372 (11251)	10664 (4174)	4.38*	ADHD > TD
VS Set Size 7	16208 (9472)	9712 (4368)	5.43*	ADHD > TD

Note. ADHD = Attention-Deficit/Hyperactivity Disorder; M = Mean; PH = Phonological; SD = Standard Deviation; TD = Typically-Developing; VS = Visuospatial

**p* < .05, ***p* < .01, ****p* < .001

Figure 1. Visual schematic of the phonological working memory task.

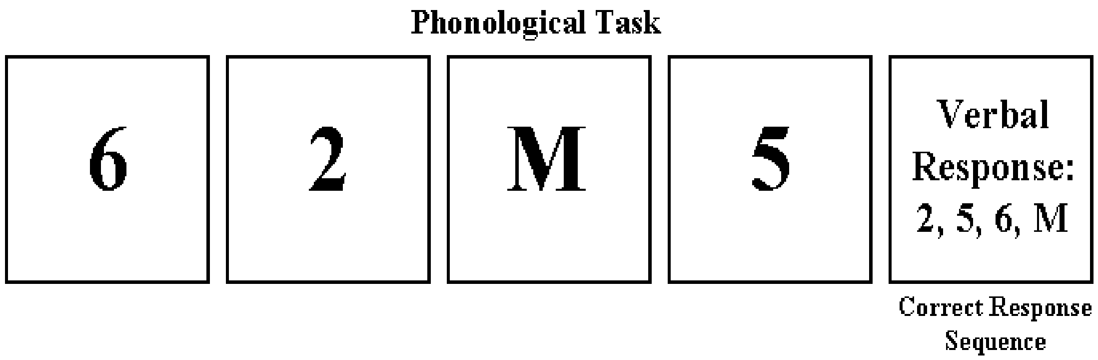


Figure 2. Visual schematic of the visuospatial working memory task.

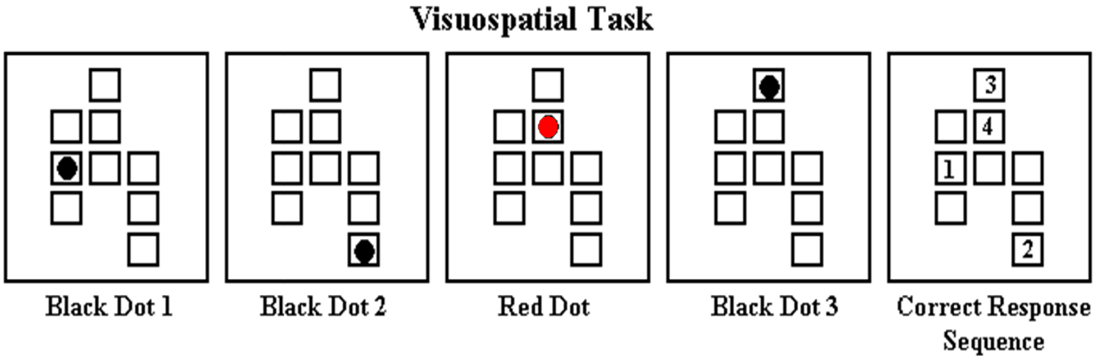


Figure 3. Comparison of activity level during visuospatial and control conditions.

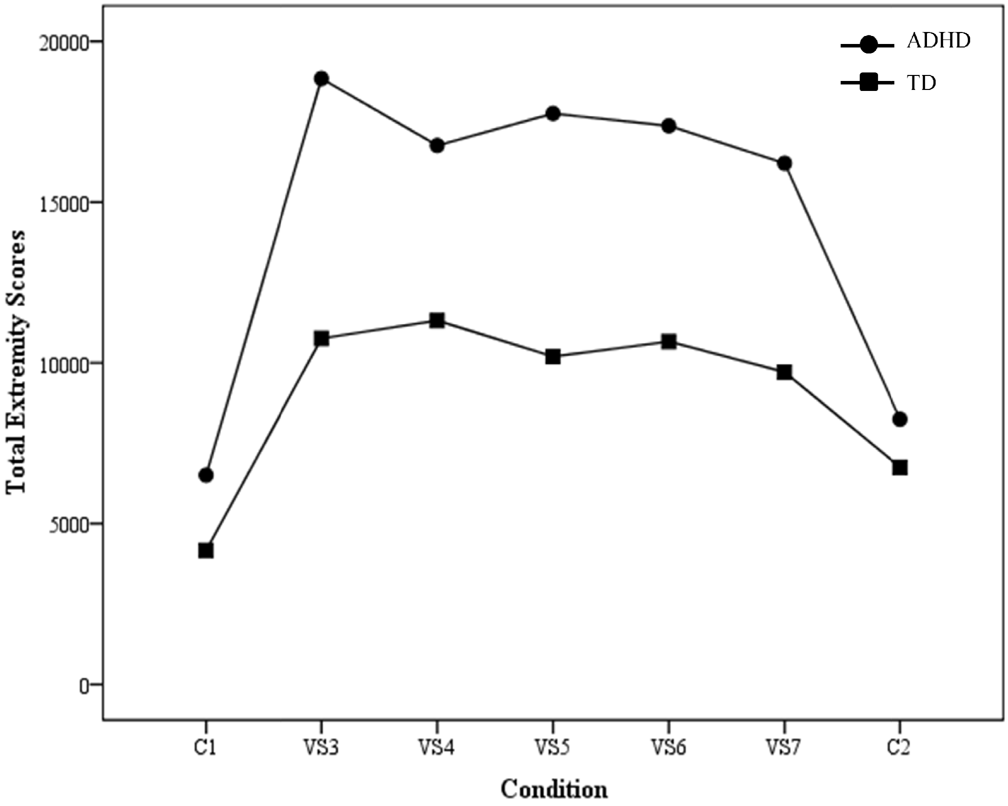


Figure 4. Working memory components examined in the latent variable analysis approach.

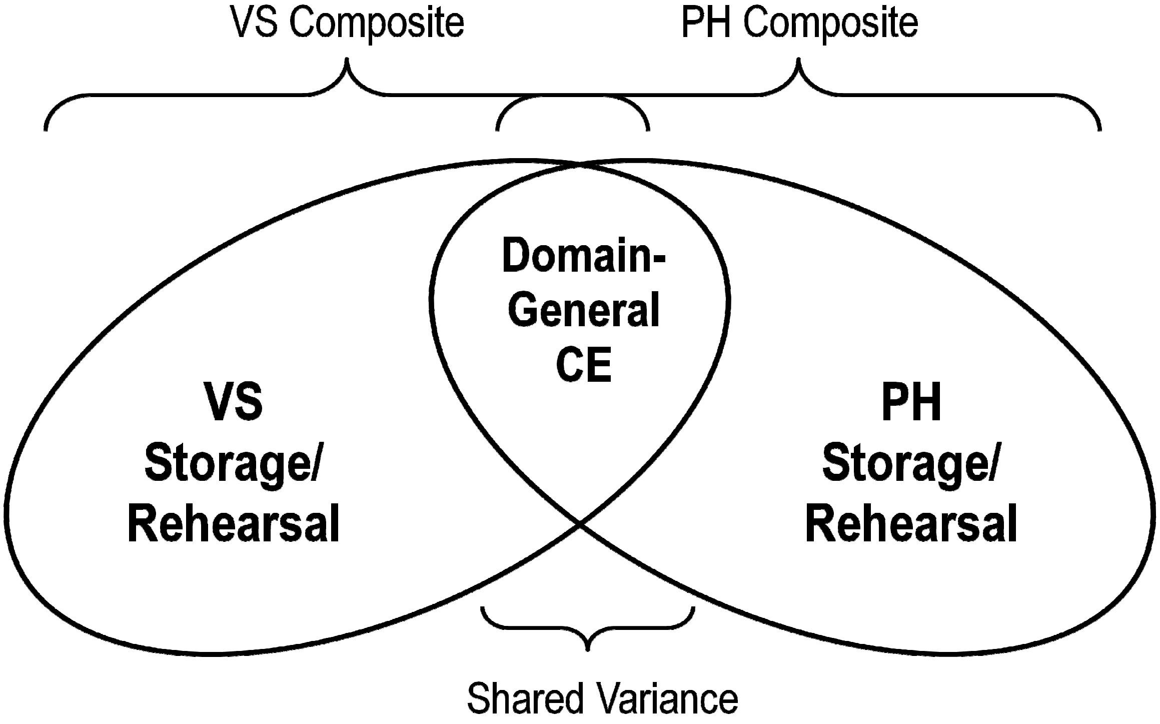


Figure 5. Visual schematic of Baddeley's (2007) working memory model.

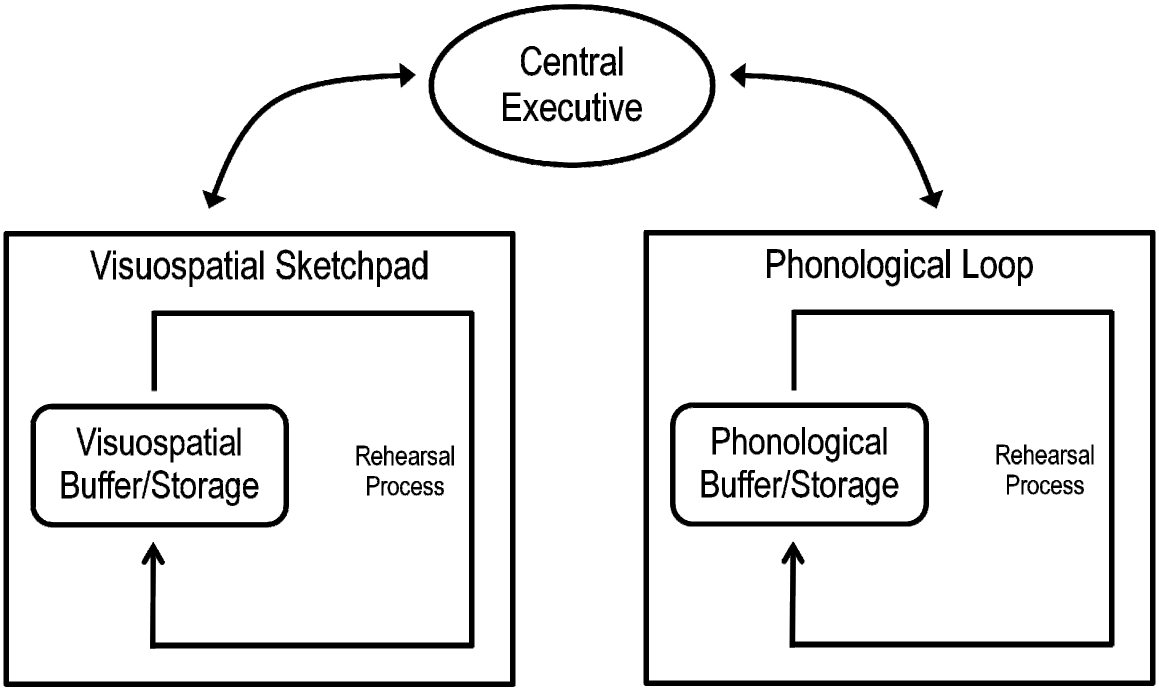
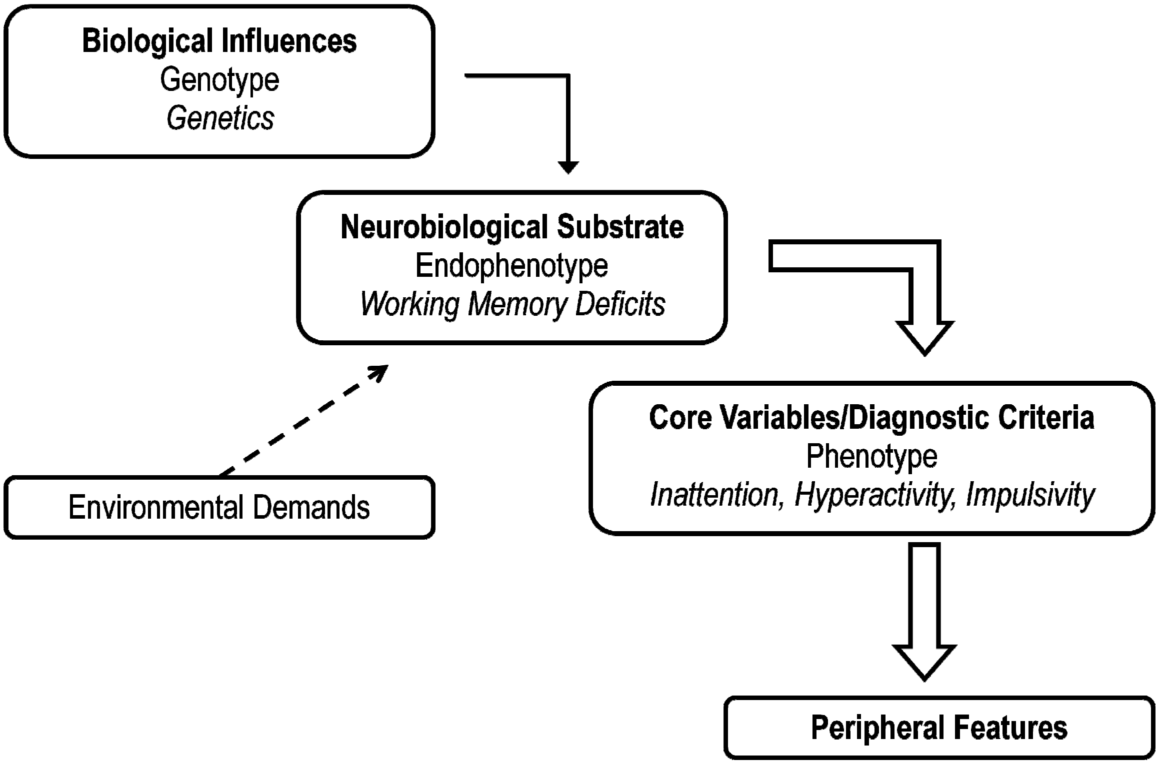


Figure 6. Working memory model of ADHD.



VITA

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Alderson, R. M. & Hudec, K. L. (2010). Hyperactivity. In S. Goldstein and J. Naglieri (Eds.), *Encyclopedia of Child Behavior and Development*. Heidelberg, German: Springer-Verlag.

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Title of Study: ATTENTION-DEFICIT/HYPERACTIVITY DISORDER (ADHD), WORKING MEMORY AND HYPERACTIVITY: AN EXAMINATION OF CORE PROCESSES IN LATE ADOLESCENTS AND ADULTS

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Scope and Method of Study: Attention-Deficit/Hyperactivity Disorder (ADHD) was originally conceptualized as a disorder of childhood, but updated research provides evidence that symptoms continue into adulthood, suggesting ADHD occurs in four to five percent of the adult population. Studies of symptom course across the lifespan have been equivocal, but executive function deficits, particularly in working memory, have been shown to persist. The working memory model of ADHD suggests that increased activity is functionally related to increased demands on the working memory system, and this connection has been supported in children. The current study examined whether objectively-measured activity level differs between young adults with ADHD and typically developing (TD) adults and whether motor activity is functionally related to working memory (WM) demands. Clinical diagnostic procedures were utilized to assign undergraduate participants into ADHD and TD groups. Actigraphs were used to obtain a measure of overall movement during phonological (PH) and visuospatial (VS) working memory tasks and control conditions.

Findings and Conclusions: All participants exhibited greater activity during phonological WM conditions compared to control conditions, yet participants in the ADHD group exhibited disproportionately greater changes in activity level compared to TD participants during visuospatial WM conditions relative to control conditions. Latent variable analysis was used to determine that activity level associated with the central executive was significantly greater in the ADHD group. Current results indicated that adults with ADHD were more active than TD controls, supporting the notion that excessive activity related to ADHD continues into adulthood. Activity differences between modalities contradict findings with children, perhaps due to developmental changes or methodological variables. This study is the first to demonstrate a functional relationship between ADHD-related activity and working memory demands, particularly on the central executive, in adults. Results are consistent with findings in children and refute the notion that excessive activity is a ubiquitous feature of ADHD unrelated to task demands.

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