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Hyperactivity In Attention-deficit/hyperactivity Disorder (adhd): Testing Functional Relationships With Phonological Working Memory Performance And Attention

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HYPERACTIVITY IN ATTENTION-DEFICIT/HYPERACTIVITY DISORDER (ADHD):
TESTING FUNCTIONAL RELATIONSHIPS WITH PHONOLOGICAL WORKING
MEMORY AND ATTENTION

by

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ABSTRACT

Excessive gross motor activity is currently considered a ubiquitous and disruptive feature of attention-deficit/hyperactivity disorder (ADHD); however, an alternative model challenges this premise and hypothesizes a functional relationship between activity level, attention, and working memory. The current study investigated whether, and the extent to which, particular forms of gross motor activity are functionally related to children's attention and phonological working memory performance. Objective observations of children's gross motor movements and attention by independent observers were conducted while children with ADHD ($n = 29$) and typically developing children ($n = 23$) completed multiple counterbalanced tasks entailing low and high phonological working memory demand. The tasks were then sequenced hierarchically to reflect the lowest to highest activity level condition for each child. Results revealed that (a) ADHD-related phonological working memory performance deficits are moderated by increases in intra-individual activity level, (b) heightened activity level impacts performance independently of changes in observed attention, and (c) increases in particular forms of movement (foot movement and out-of-chair movement) contribute to *greater* phonological working memory performance within the context of attentive behavior. The findings collectively indicate that phonological working memory deficits in children with ADHD are associated with an inability to up-regulate motor activity to facilitate optimal task performance, and that behavioral treatments targeting reductions in certain forms of hyperactivity may have unintended consequences on working memory functioning in ADHD.

This manuscript is dedicated to my God and my wife, family and friends.

"So I say to you, keep asking, and it will be given to you. Keep searching and you will find.

Keep knocking, and the door will be opened to you. For everyone who asks receives, and the one

who searches finds, and to the one who knocks, the door will be opened."

Luke 11: 9-10

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LIST OF ACRONYMS/ABBREVIATIONS

ADHD	Attention-Deficit/Hyperactivity
ANOVA	Analysis of variance
C	Control
CBCL	Child Behavior Checklist
CLC	Children's Learning Clinic
CPT	Continuous Performance Test
CSI	Child Symptom Inventory
CSI-P	Children's Symptom Inventory-Parent Version
CSI-T	Children's Symptom Inventory-Teacher Version
FSIQ	Full Scale Intelligence Quotient
K-SADS	Kiddie-Schedule for Affective Disorders and Schizophrenia
M	Mean
MTA	Multi-modal Treatment Study of ADHD
ODD	Oppositional Defiant Disorder
SD	Standard Deviation
SES	Socioeconomic Status
TD	Typically Developing
TRF	Teacher Report Form
WISC-III	Wechsler Intelligence Scale for Children – Third Edition
WISC-IV	Wechsler Intelligence Scale for Children – Forth Edition
WM	Working Memory

CHAPTER ONE: INTRODUCTION

Attention-deficit/hyperactivity disorder (ADHD) is a complex and chronic neurodevelopmental disorder whose cardinal behavioral features include developmentally inappropriate levels of inattention, impulsivity, and hyperactivity in an estimated 5-7% of children (Polanczyk, Silva de Lima, Horta, Biederman, & Rohde, 2007), with an annual cost of illness exceeding $40 billion in the United States alone (Pelham, Foster, & Robb, 2007). The emergence of hyperactivity, or excessive gross motor activity, as a primary symptom cluster and its developmental relationship with children's behavioral characteristics is inimitable. Activity level is the first enduring trait to develop in humans, and individual differences in motor activity at 28 weeks of gestation reliably predict children's motor activity in early infancy (Walters, 1965). Heightened activity level following the neonatal period is associated with desirable behavioral attributes such as positive social interactions, motor and mental maturity, and inquisitiveness (cf. Rapport, Kofler, & Himmerich, 2006, for a review). This association reverses itself rapidly during the preschool and early elementary school years, at which time children are required to regulate their gross motor activity while interacting with others and in accordance with classroom and cognitive demands. The inability to regulate gross motor activity beyond age four years predicts an ADHD clinical diagnosis at age nine (Campbell & Ewing, 1990; Palfrey, Levine, & Walker, 1985), and heightened gross motor activity after age five is associated with undesirable characteristics and outcomes such as distractibility (Adams, Finn, Moes, Flannery, & Rizzo, 2009), academic underachievement (Fergusson, Lynskey, & Horwood, 1997), aggression (Keown & Woodward, 2006; Waschbusch, 2002), and peer (Diamantopoulou, Rydell, Thorell, & Bohlin, 2007; Fischer & Barkley, 2006) and parent relationship problems (Buss, 1981). These

difficulties continue into middle childhood for a majority of children with ADHD, and set the stage for a lifetime of functional impairments despite the diminution in gross motor activity observed typically during adolescence and young adulthood for many individuals with ADHD (Biederman, Mick, & Faraone, 2000; Halperin, Trampush, Miller, Marks, & Newcorn, 2008; Hart, Lahey, Loeber, Applegate, & Frick, 1995).

CHAPTER TWO: LITERATURE REVIEW

The excessive gross motor activity exhibited by children with ADHD has been subjected to considerable empirical scrutiny for nearly a half a century using a broad range of methodologies and expanding number of innovative technologies. Early approaches relied on rating scales (Werry, 1968), direct observations (Platzman et al., 1992; Whalen et al., 1978), and grid changes (Milich, Loney, & Landau, 1982), and have been followed by technologically more sophisticated measures such as pedometers (Plomin & Foch, 1981), stabilimetric cushions (Conners & Kronsberg, 1985), actigraphs (Porrino et al., 1983), and infrared motion analysis (Teicher, Ito, Glod, & Barber, 1996). Collectively, these and more recent studies uniformly report significantly higher rates of gross motor activity in children with ADHD relative to typically developing children at home (Imeraj et al., 2011; Porrino et al., 1983), in school (Imeraj et al., 2011; Kam, Lee, Cho, Shin, & Park, 2011), while asleep (Cortese, Faraone, Konofal, & Lecendreux, 2009; Porrino et al., 1983), and while completing a diverse range of laboratory and clinical tasks (Dane, Schachar, & Tannock, 2000; Halperin, Matier, Bedi, Sharma, & Newcorn, 1992; Rapport et al., 2009) regardless of the technology employed.

Theoretical accounts of the excessive gross motor activity exhibited by ADHD have varied considerably over the years. For example, a prominent model describes hyperactivity as ubiquitous, non-goal oriented motor movement that reflects children's effort to inhibit task irrelevant behavior and regulate goal-directed behavior (Barkley, 1997), whereas a more recent model considers it a manifestation of subcortical impairment that remains relatively static throughout life and is unrelated to executive functions such as working memory (Halperin & Schulz, 2006; Halperin et al., 2008). Only one of the contemporary models hypothesizes a

functional role for the higher rates of gross motor behavior observed in children with ADHD, wherein hyperactivity serves one of two primary purposes: to augment their well-documented prefrontal cortical hypoactivation while engaged in academic (Mann, Lubar, Zimmerman, & Muenchen, 1992) and cognitive (Clark, Maisog, & Haxby, 1998; Dickstein, Bannon, Castellanos, & Milham, 2006; El-Sayed, Larsson, Persson, & Rydelius, 2002) activities that place demands on working memory (WM); and in a more limited number of situations, to terminate the perceived aversiveness associated with these types of activities by escaping from them (Rapport, Chung, Shore, & Isaacs, 2001; Rapport, Kofler, Alderson, & Raiker, 2008).

The diverse predictions stemming from the three models concerning the role of excessive gross motor activity in children with ADHD relative to typically developing (TD) children were investigated in a recent experimental study which utilized actigraphs to record children's movements 16 times per second across three placement sites while they completed tasks with minimal or high WM demands (Rapport et al., 2009). All children exhibited significantly higher rates of movement under the high-demand relative to low-demand WM conditions; however, the magnitude difference between children with ADHD and TD children was 3.03 standard deviations under the high WM demand condition tasks, but not significantly different under the low demand conditions consistent with WM model predictions.

Despite the methodological rigor and use of high precision actigraphs to measure children's gross motor activity, Rapport and colleagues (2009) were unable to test directly several functional WM model predictions regarding whether higher rates and specific forms of movement are associated with improved attention and/or WM performance or impair these interrelated aspects of cognitive functioning consistent with alternative model predictions.

Understanding the complex interrelationships among these variables is particularly critical for clinical/school psychologists and other mental health professionals charged with designing, implementing, and monitoring psychosocial treatments for children with ADHD in home and school settings. For example, empirically supported psychosocial interventions such as those used in the large-scale, multi-site MTA treatment outcome study of children with ADHD (Jensen et al., 2001; Molina et al., 2009) include a wide range of contingencies to address the disruptive behavior and functional impairments typically exhibited in the classroom, including specific consequences for staying seated as a means to reduce excessive gross motor activity. Other behavioral interventions have used a more direct approach, such as having children wear actigraphs that emit visual and vibration feedback whenever children's gross motor activity decreases to a pre-determined level, with positive contingencies administered for reduced movement (Tryon, Tryon, Kazlausky, Gruen, & Swanson, 2006).

The indirect or direct targeting of children's excessive gross motor activity reflects the assumption that *hyperactivity* interferes with children's ability to actively engage in and complete learning related activities such as classroom assignments and homework within the school and home settings, respectively. Such recommendations would be counter-indicated, however, if ADHD-related increased motor activity is functional—that is, necessary for maintaining alertness while engaged in learning-related activities that routinely place greater demands on executive functions such as WM.

The present study is the first to address one of the pivotal issues concerning the excessive gross motor activity exhibited by children with ADHD by testing several hypotheses regarding whether, and the extent to which, particular forms of gross motor movements exhibited by children with ADHD are functionally related to their attention and WM performance. To

accomplish this goal, multiple forms of gross motor movements and children's attention were recorded continuously while children with ADHD and typically developing children completed tasks with minimal and high WM demands in a controlled experimental setting that has been shown to evoke rates of inattentive behavior similar to rates observed in regular classroom settings (Kofler, Rapport, & Alderson, 2008; Kofler, Rapport, Bolden, Sarver, & Raiker, 2010). All children were expected to exhibit significantly higher rates of gross motor activity while performing high-WM demand relative to low-WM demand tasks, and children with ADHD were expected to exhibit higher rates of motor activity and less attentive behavior relative to typically developing (TD) children across all conditions consistent with WM model predictions and the findings of previous studies using direct observations (Abikoff et al., 2002) and actigraphs to assess activity level (Dane et al., 2000; Rapport, Bolden et al., 2009). Changes in attentive behavior were expected to moderate the relationship gross motor activity and WM performance among children with ADHD, whereas no prediction regarding functional contributions among attention and movement were made for TD children. This prediction was based on WM hypotheses regarding the potentially facilitative role of hyperactivity in maintaining alertness to task demands. Both groups were also compared on the multiple forms of gross motor movement used in the study to address the hypothesis that shifts in the topography of movement may distinguish both groups during high-WM demand conditions. Finally, the relative contributions of children's specific gross motor movements were examined as predictors of the relationship between phonological WM performance and attentive behavior to address the competing beliefs that hyperactivity detracts from or contributes to task performance by means of task engagement.

CHAPTER THREE: METHOD

Method

Participants

The sample included 52 boys aged 8 to 12 years recruited by or referred to the Children's Learning Clinic (CLC) through community resources (e.g., pediatricians, community mental health clinics, school system personnel, and self-referral). The CLC is a research-practitioner training clinic known to the surrounding community for conducting developmental and clinical child research and providing *pro bono* comprehensive diagnostic and psychoeducational services. Its client base consists of children with suspected learning, behavioral or emotional problems, as well as typically developing children (those without a suspected psychological disorder) whose parents agree to have them participate in developmental/clinical research studies. A psychoeducational evaluation was provided to the parents of all participants.

Two groups of children participated in the study: children with ADHD and typically developing children without a psychological disorder. Sample ethnicity was mixed and included 34 white non-Hispanic (65%), 12 Hispanic English-speaking (23%), 2 African American (4%), and 4 children of mixed racial/ethnic background (8%). All parents and children gave their informed consent/assent to participate in the study in accordance with the university's Institutional Review Board approved the study prior to the onset of data collection.

Group Assignment

All children and their parents participated in a detailed, semi-structured clinical interview using the Kiddie Schedule for Affective Disorders and Schizophrenia for School-Aged Children (K-SADS; Kaufman et al., 1997). The K-SADS assesses onset, course, duration, severity, and impairment of current and past episodes of psychopathology in children and adolescents based

on DSM-IV criteria. Its psychometric properties are well established, including inter-rater agreement of .93 to 1.00, test-retest reliability of .63 to 1.00, and concurrent (criterion) validity between the K-SADS and psychometrically established parent rating scales (Kaufman et al., 1997).

Twenty-nine children met the following criteria and were included in the ADHD-Combined Type group: (1) an independent diagnosis by the CLC's directing clinical psychologist using DSM-IV criteria for ADHD-Combined Type based on K-SADS interview with parent and child which assesses symptom onset, presence, and severity across home and school settings; (2) parent ratings of at least 2 *SD*s above the mean on the Attention Problems clinical syndrome scale of the Child Behavior Checklist (CBCL; Achenbach & Rescorla, 2001) or exceeding the criterion score for the parent version of the ADHD-Combined subtype subscale of the Child Symptom Inventory (CSI; Gadow, Sprafkin, & Salisbury, Schneider, & Loney, 2004); and (3) teacher ratings of at least 2 *SD*s above the mean on the Attention Problems clinical syndrome scale of the Teacher Report Form (TRF; Achenbach & Rescorla, 2001) or exceeding the criterion score for the teacher version of the ADHD-Combined subtype subscale of the CSI (Gadow et al., 2004). The CSI requires parents and teachers to rate children's behavioral and emotional problems based on DSM-IV criteria using a 4-point Likert scale. The CBCL, TRF, and CSI are among the most widely used behavior rating scales for assessing psychopathology in children, and their psychometric properties are well established (Rapport, Kofler, Alderson, & Raiker, 2008). All children in the ADHD group met criteria for ADHD-Combined Type, and 8 (28%) met criteria for comorbid Oppositional Defiant Disorder (ODD).

Twenty-three children met the following criteria and were included in the typically developing group: (1) no evidence of any clinical disorder based on parent and child K-SADS

interview; (2) normal developmental history by maternal report; (3) ratings below 1.5 *SD*s on the clinical syndrome scales of the CBCL and TRF; and (4) parent and teacher ratings within the non-clinical range on all CSI subscales. Typically developing children were recruited through contact with neighborhood and community schools, family friends of referred children, and other community resources.

Children presenting 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. Ten children had been prescribed psychostimulants previously; eight children were prescribed psychostimulants currently, which were withheld for a minimum of 24 hours prior to participating in all assessment sessions after consulting with their prescribing physician.

Measures

Phonological Working Memory.

The phonological WM task is similar to the Letter-Number Sequencing subtest on the WISC-IV (Wechsler, 2003), and assesses phonological WM based on Baddeley's (2007) model. Children were presented a series of jumbled numbers and a capital letter on a computer monitor. Each number and letter (4 cm height) appeared on the screen for 800 ms, followed by a 200 ms inter-trial stimulus interval. The letter never appeared in the first or last position of the sequence to minimize potential primacy and recency effects, and was counterbalanced across trials to appear an equal number of times in the other serial positions (i.e., position 2, 3, 4, or 5). Children were instructed to recall the numbers in order from smallest to largest, and to say the letter last (e.g., 4 H 6 2 is correctly recalled as 2 4 6 H; see Figure 1). Children were allowed a total of 2 s per stimulus during the response phase during which they were required to respond orally. The

last response was followed by an inter-trial interval of 1 s and an auditory chime that signaled the onset of a new trial.

Each child was administered the phonological task at four different cognitive loads (i.e., phonological set sizes consisting of 3, 4, 5, and 6 stimuli) across the four testing sessions. The four WM memory set size conditions each contain 24 unique trials of the same stimulus set size, and were counterbalanced across the four testing sessions to control for order effects and potential proactive interference effects across set size conditions (Conway et al., 2005). Five practice trials were administered before each task and children were required to achieve 80% correct before advancing to the full task (Rapport et al., 2008). Previous studies of ADHD and typically developing children indicate large magnitude between-group differences on these tasks (Rapport, Alderson, et al., 2008), and performance on these tasks predict ADHD-related impairments in actigraph-measured activity level (Rapport et al., 2009), observed attentive behavior (Kofler et al., 2010), and impulsive behavior (Raiker, Rapport, Kofler, & Sarver, 2012). Evidence for reliability and validity of the four WM tasks includes high internal consistency (α = .82), and demonstration of the expected magnitude of relationships (Swanson & Kim, 2007) with an established measure of short-term memory (WISC-III or -IV Digit Span raw scores: r = .52 to .64). Two trained research assistants, blind to children's diagnostic status and seated in an adjacent room, listened to children's verbal responses through headphones and independently recorded the number/letter stimuli for all trials within the four set size conditions. Inter-rater reliability based on percentage agreement was 96.30%.

Performance data was calculated using a partial-credit scoring approach due to its preferred psychometric properties (Conway et al., 2005), and converted to the percentage of stimuli correct per trial to account for differences in the number of stimuli available for recall across the set

sizes.[1] The dependent variable used for purposes of analysis was the percentage of stimuli correct per trial.

Control (C) conditions.

Children's attention and motor behavior was quantified while they used the Microsoft® Paint program for five consecutive minutes both prior to (C1) and after (C2) completing the phonological WM tasks during four consecutive Saturday assessment sessions. The Paint program allows children to draw/paint anything they like on the monitor using a variety of interactive tools, and served as pre and post conditions to assess and control for demand characteristics (e.g., interacting with the same computer in the same room in the same chair), and potential within-day fluctuations in attentive and motor behavior (e.g., fatigue effects). The program was also selected to provide an experimental means by which to make comparisons between tasks that place minimal demands and substantial demands on phonological WM resources (Baddeley, 2007). Attentive and gross motor behavior during the four pre and four post control conditions were averaged separately to create pre- and post-control condition composite scores based on preliminary analyses that revealed no significant differences in children's pre/post overall attention and activity level across sessions ($p > .05$).

Behavioral Codes

A ceiling-mounted digital video camera was used to record children's attentive behavior and gross motor activity while completing each of the tasks described above. All recordings were downloaded subsequently and coded independently by two trained observers blind to children's diagnostic status using Observer XT 10.0 (Noldus Information Technology, 2003) computer

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[1] Partial-credit scoring credits each stimulus responded to correctly if it is emitted in the correct sequence of a response. It differs from an all-or-nothing scoring approach which counts a given trial correct only if all stimuli within the trial are emitted in the correct sequence. The former approach is associated with significantly higher internal consistency relative to the latter approach (Conway et al., 2005).

software. Overall inter-rater percent agreement across all experimental conditions for the behavioral codes was high (97.62%).

Attentive behavior.

Visual attention to task was coded as a continuous variable to quantify attentive behavior exhibited while children were oriented to and not oriented to the experimental tasks. Observers coded behavior into one of two mutually exclusive states. Children were coded as oriented to task (i.e., attentive) whenever their head was directed within 45° vertically/horizontally of the center of the computer monitor on which the task is displayed. Children were coded as not oriented for each occasion when their head direction exceeded a 45° vertical/horizontal tilt away from the center of the monitor for greater than two consecutive seconds during the tasks. The oriented and not oriented codes used in the present study are analogous to on- and off-task definitions used in most laboratory and classroom observation studies (Kofler et al., 2008).

Gross motor behavior.

Chair movement.

Chair movement was coded as a continuous variable and used to quantify three types of chair movements while children are seated during the experimental tasks described above. Three mutually exclusive states of chair movement were coded based on movement occurring relative to imagined stationary axes extending from the child to the computer monitor and 90 degrees left and right of the child (see Figure 2). *Swinging* included all chair movements that cross fewer than three stationary axes in a continuous motion (i.e., ≤ 180 degrees). *Spinning* included movements that cross three or more fixed axes in a continuous motion defined as intersecting at a 90 degree angle (i.e., > 180 degrees). *Auxiliary chair movement* included all other forms of chair movements exclusive of those described above (e.g., moving the chair forward and backwards

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while seated or leaning back in the chair). It should be noted that all three forms of chair movement always correspond with either an oriented or non-oriented state despite representing independent forms of behavior.

Out-of-chair movement.

Out-of-chair was coded as a continuous variable to quantify the proportion of time children were in and out of their chair during an experimental task. *In-chair* was coded whenever a child's buttocks and/or a knee were in physical contact with the chair seat, or the child was sitting on his legs, hands, or feet in the chair. Its mutually exclusive inverse, *Out-of-chair*, was coded any time that a child's buttocks and/or both knees were not in physical contact with the chair seat.

Foot movement.

Foot movement was coded as a continuous variable and used to quantify all observable incidences of foot and ankle movement (e.g., foot tapping, fidgeting, foot/feet swinging) that occurred for greater than two consecutive seconds. Observers were trained not to code foot/ankle movements that occurred within the context of an active Chair Movement state unless the child moved his feet or ankles during the course of a chair movement (e.g., wriggling feet while spinning in the chair). This procedure was followed to preserve the distinction between chair and foot movement codes.

Measured Intelligence

All children were administered the Wechsler Intelligence Scale for Children third or fourth edition to obtain an overall estimate of intellectual functioning based on each child's estimated Full Scale IQ (FSIQ; Wechsler, 1991; 2003). The changeover to the fourth edition was due to its

release during the conduct of the study and to provide parents with the most up-to-date intellectual evaluation possible.

Procedures

The phonological task was programmed using SuperLab Pro 2.0 (2002). All children participated in four consecutive Saturday assessment sessions. The phonological task was administered as part of a larger battery of neurocognitive tasks that required the child's presence for approximately 2.5 hours per session. All tasks were counterbalanced across testing sessions to minimize order effects. Children completed all tasks while seated alone in an assessment room with the door ajar. All children received brief (2-3 min) breaks following each task, and preset longer (10-15 min) breaks after every two to three tasks to minimize fatigue. Children were seated in a caster-wheel swivel chair approximately 0.66 m from the computer monitor for all tasks.

Dependent Variables

The primary dependent variables were the proportion of each task (i.e., % of task duration) children exhibited attentive behavior (i.e., were oriented), overall gross motor behavior (i.e., were engaged in any of the five coded movements, collectively), or any one of the individual gross motor behaviors during each of the control (C1, C2) and hierarchically arranged activity level conditions (Activity Level 1-4) described below. The percentage of stimuli correct per trial was used to index phonological WM performance during each of the Tier I, II, III, and IV analyses.

CHAPTER FOUR: DATA ANALYTIC APPROACH

Children's intra-individual overall gross motor movement (i.e., percentage of time engaged in any of the five coded movements, collectively) across the four phonological WM set size conditions was examined initially and sequenced hierarchically such that the four conditions represented the lowest to highest activity level condition for each child (Activity Level conditions 1-4, respectively). The percentage of stimuli identified correctly for each of the four WM set-size conditions (i.e., 3-, 4-, 5-, or 6-stimuli) was calculated for each child, and the unique data for each of the four conditions was assigned successively to an activity level condition based on the percentage of overall movement the child exhibited during that specific set-size condition. For example, if a child correctly identified 68% of the stimuli in the phonological set size four condition and exhibited the lowest rate of movement under this condition relative to the three other WM set size conditions, the performance data was assigned to the Activity Level 1 (lowest movement) condition. The procedure was followed until each child's performance data for each of the four phonological set size conditions was assigned exclusively to one of the four activity level conditions. This approach allowed the full range of experimental conditions to be used, thus capitalizing on increased power to test the central hypotheses regarding the interrelationships among children's gross motor activity, phonological WM performance, and attention.

CHAPTER FIVE: RESULTS

Results

Preliminary Analyses

All variables were screened for univariate/multivariate outliers and tested against $p <$ 0.001. The overall gross motor movement score at the highest activity set size for one child in the ADHD group was replaced with a value equal to one percentage point greater than the next most extreme score for the group. No other univariate or multivariate outliers were identified. Partial observational data was available for four children with ADHD due to video malfunction (i.e., unavailable data included 1 child's set size 3 condition, 1 child's set size 4 condition, 2 children's set size 6 condition, and 1 child's post-control condition) and replaced with the ADHD group mean for the specific set size or control task condition in which the video failed to record based on recommendations (Tabachnick & Fidell, 2007). The results and interpretation of analyses presented below remained unchanged when including or excluding these four cases. All parent and teacher behavior rating scale scores were significantly higher for the ADHD group relative to the TD group as expected (see Table 1). Children with ADHD and TD children did not differ significantly on Hollingshead (1975) SES scores ($p = .19$) or FSIQ ($p = .24$); however, children with ADHD were marginally younger than TD children ($p < .01$). Age was not a significant covariate for any of the Tier I, II, II, or IV analyses (all p values $\geq .13$). Therefore, the simple model results are reported with no covariates.

Tier I: Intra-individual Differences in Activity Level

An initial set of analyses was conducted to examine the internal validity of the hierarchically sequenced movement conditions by verifying that (a) activity level set size was not confounded by phonological WM set size demands such that the reordered activity level

conditions occurred disproportionately across the four phonological WM set size conditions based on group membership; and (b) higher rates of movement were exhibited under the four activity level conditions relative to the pre- and post-control conditions.

An omnibus chi-square test revealed that the overall distribution of the number of children across both groups was not significantly different with regard to the set size in which children's least through most active conditions were categorized ($\chi^2(3) = 0.20$, $p = .97$). This finding substantiates that sequencing the conditions based on activity level was not confounded by differences associated with WM set size demands.

A group (ADHD, TD) by condition (pre-control, post-control, activity level set sizes) mixed-model ANOVA was conducted to examine whether the overall percentage of movement for both groups was greater under the four phonological WM activity level conditions relative to the two control conditions as hypothesized. Results revealed significant main effects for group ($F(1, 50) = 10.35$, $p = .002$, $\eta_p^2 = .17$) and condition ($F(5, 250) = 206.30$, $p < .001$, $\eta_p^2 = .81$), and a non-significant interaction effect ($F(5, 250) = 0.62$, $p = .69$). LSD post hoc contrasts revealed that children with ADHD were more active than TD children across all experimental conditions ($p = .002$). Both groups exhibited significantly higher percentages of movement under the four phonological WM activity level conditions relative to pre/post-control conditions (all p values < .001), and children exhibited significantly more gross motor movement during each of the hierarchically sequenced activity level set sizes as expected (all p values < .001). Results are depicted in Figure 1.

Tier II: Impact of Activity Level

Mixed-model ANOVAs with LSD post hocs were conducted separately to examine whether the increasing activity level set size conditions were associated with group differences

(ADHD, TD) in phonological WM performance and attention during these same conditions. Control conditions (C1, C2) were not included in the foregoing analyses because they have no associated performance data.

Phonological working memory performance.

The mixed-model ANOVA examining the association between children's activity level and phonological WM performance revealed significant main effects for group ($p < .001$) and activity level ($p = .03$), and a significant group by activity level interaction ($p = .002$). LSD post hoc tests for the interaction revealed a large magnitude between-group difference in phonological WM performance under the two lowest activity level set size conditions ($d = 1.33$-1.47, p values $< .001$), which was no longer significant under the two highest activity level conditions ($d = 0.52$-0.36, p values $= .07$-$.21$) due to divergent patterns of performance between the two groups (see Figure 2). For TD children, phonological WM performance was not significantly different among most activity level set sizes with the exception of the third most active condition, which was significantly lower relative to the two least active conditions. An analysis of trend indicated a significant overall linear pattern of declining performance associated with activity level for the TD group ($F(1,22) = 6.14$, $p = .02$, $\eta_p^2 = .24$) and the magnitude of performance decreases between the least and most active conditions was 0.82 SD units. In contrast, phonological WM performance among children with ADHD was significantly greater under the most active condition relative to the three lower activity level conditions, which were not significantly different from each other (all p values $\geq .08$). An analysis of trend confirmed that the association was characterized primarily by a linear pattern ($F(1,28) = 6.14$, $p = .02$, $\eta_p^2 = .18$), and to a lesser extent by a quadratic effect ($F(1,28) = 8.43$, $p = .007$; $\Delta \eta_p^2 = .05$), wherein children with ADHD performed similarly under the lowest activity level conditions followed by a linear increase of

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40% at their apogee. The magnitude of performance increases between the least and most active conditions for children with ADHD was 0.87 *SD* units, which is nearly identical to the value obtained for the TD children, but in the opposite direction. Results are depicted in Table 2 and Figure 2.

Attention.

The mixed-model ANOVA examining the association between activity level and children's attention revealed a significant main effect for group ($p < .001$), wherein TD children exhibited higher rates of attentive behavior relative to children with ADHD under all activity level conditions. Neither the main effect for activity level ($p = .10$) nor the group by activity level interaction ($p = .25$) were significant. The LSD post hoc test indicated that the average magnitude difference in attention between children with ADHD and TD children across all activity level conditions was 1.6 *SD* units. Results are depicted in Table 3 and Figure 2.

Tier III: Topographical Changes in Movement

An examination of between-group differences in children's gross motor activity was conducted to identify whether the impact of activity level in Tier II could be explained by systematic changes in specific types of movements associated with activity level for children with ADHD and TD, based on WM model hypotheses regarding the function of movement and the relationship to its topography.

A series of mixed-model ANOVAs was repeated with each of the five movement categories separately using the percentage of the task engaged in each behavior as the dependent variable. The results indicated that four of the five movement categories coded were significantly different between children with ADHD and TD children. Children with ADHD exhibited significantly higher rates of chair spinning ($p = .003$), foot movement, ($p < .01$) and auxiliary

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chair movement ($p < .001$), relative to typically developing children across the four activity level set size conditions. Effect size computation indicated that these differences were moderate to large in magnitude (ds = 0.77- 1.01). Both groups, however, exhibited similar levels of chair swinging movement ($p = .86$) and being out of their chair ($p = .09$). For all children, higher activity level conditions were associated with an increase in the rate of chair swinging ($p < .001$) and foot movement ($p < .001$), but not chair spinning, auxiliary chair movement, or out of chair movement (p values = .17-.84). The group by activity level interactions for the five coded movements were non-significant (p values = .09-.54). Collectively, the pattern of between-group differences indicates that heightened rates of chair spinning, foot, and auxiliary chair movements were the specific forms of movement responsible for distinguishing the groups under the hierarchically ordered activity level conditions in Tier II. The increases observed in overall movement for all children across these conditions reflected specific increases in chair swinging and foot movement. Descriptive results for each movement category are presented in Table 4.

Tier IV: Predicting Attention-related Performance

Tier IV examined the WM model prediction that increased movement associated with WM demands engenders increased performance through corresponding attentive behavior, and evaluates the extent to which this may reflect specific movement behaviors. This was accomplished by examining the independent contributions of changes in children's intra-individual gross motor behavior to performance in a multiple regression with each movement category's intra-individual change included as a predictor.

To examine WM model predictions, latent variable techniques were used to construct latent indicators reflecting phonological WM performance that was directly related to attention. This was accomplished using a 3-step approach. Children's attentive behavior scores and

phonological WM performance scores were first regressed onto each other separately at each of four activity level set size conditions. Predicted scores were retained to reflect the shared variance between performance and attentive behavior.[2] The four latent predicted scores were averaged together subsequently to form a composite score reflecting overall performance associated with attention which was used as the dependent variable in the regression analysis. Difference scores for each gross motor behavior between the least and most active conditions were used to index change in activity level.[3]

Performance related to attentive behavior.

The multiple regression analysis with increases across the five individual movement behaviors entered simultaneously as predictors of the latent variable measuring performance associated with attentive behavior was significant ($F(5,46) = 3.60$, $p = .008$, $R^2 = .38$). Increases in foot movement ($\beta = 0.47$, $p = .008$) and out of chair movement ($\beta = 0.32$) independently predicted significantly *greater* phonological WM performance associated with attentive behavior. Increases in chair spinning, chair swinging, and auxiliary chair movement did not significantly predict performance (all p values > .34). Collectively, these results reveal that increases in feet movement and out of chair movement that occur in the context of attentive behavior are associated with WM performance increases that are moderate in magnitude.

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[2] The relationship between phonological working memory performance and attentive behavior was significant for all activity level set size conditions ($p = .02$-.001; $R^2 = .22$, .55, .10, & .10, respectively for the least to most active conditions). Extracting shared variance is preferable to alternative aggregation techniques due to the former's ability to reflect only common variance among measures, resulting in 100% reliable and error-free estimates of children's performance that was associated with attentive behavior (Tabachnick & Fidell, 2007).

[3] The use of change scores between the least to most active condition is supported by the predominantly linear effects between heighted activity level and phonological performance among TD and ADHD children reported in Tier II.

CHAPTER SIX: DISCUSSION

This is the first study to test whether the phonological working memory (WM) performance and objectively measured attentive behavior of children is related functionally to concurrent gross motor activity. The overall gross motor activity of children with ADHD and typically developing children was measured during four tasks that imposed active phonological WM demands. Tasks were ordered in a hierarchical sequence according to each child's overall activity level to determine whether increases in intra-individual activity level were associated with group differences in phonological WM performance and attention. Overall, children with ADHD exhibited higher rates of overall gross motor activity and lower rates of attentive behavior relative to typically developing children during all experimental conditions. These findings are consistent with a robust literature documenting ADHD-related hyperactivity and impaired attention across a diverse range of settings, contexts, demands, and measurement methodologies (Halperin et al., 2002; Imeraj et al., 2011; Kam et al., 2011; Kofler, Rapport, & Alderson, 2008; Lauth et al., 2006; Platzman et al., 1992; Rapport et al., 2009; Tiecher et al., 1996).

A principal finding of the investigation was that the large magnitude WM performance deficits for children with ADHD relative to TD children during the two least active conditions ($d = 1.33\text{-}1.47$) were no longer evident during the two most active gross motor activity conditions, and that this effect was driven by divergent relationships between heightened activity level and performance between the two groups. Specifically, increased intra-individual gross motor activity among children with ADHD was associated with robust *increases* in WM performance ($d = .87$) among children with ADHD, whereas TD children evidenced similar magnitude

decreases ($d = .82$) in WM performance as a function of increased gross motor activity such that between-group differences were no longer significant when children were most active (83% vs. 77% for the TD and ADHD groups, respectively). The WM performance deficits observed in children with ADHD relative to TD children under the lower gross motor activity conditions are consistent with those reported in previous experimental investigations (Bolden et al., 2012; Rapport et al., 2008) and meta-analytic reviews (Kasper et al., 2013; Martinussen et al., 2005; Willcutt et al., 2005), and extends the extant literature by demonstrating that the magnitude of impairment may vary and diminish considerably as a function of children's gross motor activity.

The possibility that systematic changes in children's WM performance across the gross motor activity conditions may be an artifact and occur secondarily to changes in their observed attention was scrutinized based on previous findings demonstrating a significant relationship between increased WM cognitive demands and decreased attention in children with ADHD (Kofler et al. 2010). This explanation was unsupported, however, based on the non-significant changes in attention for both groups across the four activity level conditions. Direct observations of children's oriented behavior during other types of cognitive tasks such as the continuous performance test (CPT) have also been reported (Borger & van der Meere, 2000), wherein children with ADHD engaged in more non-oriented behavior than TD children but without compromising their performance efficiency. The primary discrepancy with the current investigation's findings is that Borger and van der Meere (2000) reported that movement away from the task occurred disproportionately during periods of inattention, whereas movement increased independent of attention in the current study. The discrepant results may reflect the differences in cognitive load between the two tasks, as well as the underlying cognitive processes required for their successful execution. For example, the CPT used by Borger and van der Meere

(2000) required children to simply identify the letter 'Q' and ignore the letter 'O' whenever stimuli appeared on the screen, which represents a simple visual recognition task with a minimal cognitive load relative to the 3- to 6-stimulus set size conditions used in the current investigation. The additional requirement of having to briefly store/rehearse and manipulate these stimuli mentally is also associated with significantly greater cognitive demands specific to the WM system, and accentuated by the nominal concurrent validity ($r = .20$) between continuous performance and WM span tasks (Kane et al., 2008; Redick & Lindsey, 2013).

When specific types of motor activity were examined, between-group differences in overall gross motor activity were associated with higher rates of chair spinning, foot movement and auxiliary chair movement within the ADHD group, and increases in overall movement for both groups were associated with increases in chair swinging and foot movement behaviors. Collectively, these findings are consistent with WM model predictions regarding topographical changes in movement postulated to occur when engaged in activities that place demands on children's WM. The findings are also consistent with previous observational studies documenting elevated rates of specific motor behaviors in children with ADHD within their regular education classrooms while completing academic seat-work activities (Abikoff et al., 2002). Findings from the MTA study, for example, indicated that children with ADHD exhibited greater levels of fidgety movement, out-of-seat behavior, in-seat minor movement such as rocking (similar to the auxiliary chair movement category used herein) and 'vigorous' motor behavior (Abikoff et al., 2002). Finally, the observation that children with ADHD were distinguished from TD children on both infrequently (out-of-chair) and commonly (foot movement) observed forms of movement attests to the utility of incorporating a comprehensive

behavioral observation schema to assess children's gross motor activity (Platzman et al., 1992; Rapport et al., 2006; Volpe, DiPerna, Hintze, & Shapiro, 2005).

The hypothesis that activity level contributes functionally to task performance by augmenting attention processes at first seems unsupported given that rates of attention did not increase with changes in gross motor activity. However, changes in two specific motor behaviors that were disproportionately exhibited by children with ADHD—foot movement and out-of-chair movement—contributed to *greater* phonological WM performance when a combined latent measure consisting of performance and attention was used. This finding has important implications for parents, teachers, and clinicians as it challenges prevailing views that children's excessive motor activity is uniformly associated with impaired cognitive performance. Rather, our findings indicate that children's phonological WM performance benefited from increased foot and out-of-chair movement within the context of being attentive—that is, cognitive performance improved when increases in particular forms of movement occurred while paying attention.

Considering that heightened activity level contributed to phonological WM performance only when associated with attentive behavior, the current findings potentially shed light on a mechanism for the effect of increased cortical activity associated with increased motor movement (Zentall, 1980). That is, the results imply that if children are attending to a learning-related activity that requires WM processes, increased activity level may help regulate children's internal focus of attention, one of three central executive WM processes. The internal focus of attention is employed when required information must be retrieved from memory and processed cognitively without the benefit of external visual cues while minimizing potential internal/external effects that may interfere with this process (Garavan 1998; Oberauer 2003).

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This may help explain the diminution in motor activity (Swanson et al., 2002) and increased cognitive performance (Berridge & Devilbiss, 2011) achieved typically with psychostimulant medications, which are known to increase autonomic arousal (Berridge & Devilbiss, 2011; Lawrence et al., 2005). The hypothesis is also supported by the well-documented finding that psychostimulants improve or normalize direct observations of classroom attention in approximately three-fourths of children with ADHD when individually titrated (Rapport, Denney, DuPaul, & Gardener, 1994) but fails to translate into improved academic functional outcomes for a majority of children (Molina et al., 2009).

Limitations

Several caveats merit consideration when considering the present findings. Independent replication with larger samples that include females, older and younger children, and other ADHD subtypes is needed to address the degree to which our results generalize to the larger ADHD population. It will also be important to examine the extent to which heightened activity level coupled with attentive behavior may contribute positively to task performance on other neurocognitive tasks, and most importantly, in classroom settings. Examination of tasks that rely heavily on visuospatial rather than phonologically-based WM abilities will be particularly important to determine whether the tripartite relationship among particular forms of gross motor activity, attention, and cognitive performance holds when the visuospatial WM subsystem is utilized. This caveat is based on previous studies demonstrating that some forms of increased movement may impair performance on visuospatial WM tasks (Lawrence, Myerson, Oonk, & Abrams, 2001). Despite evidence that ADHD-related phonological WM deficits are moderated by the intra-individual activity level, it is unknown whether the findings reflect the entire phonological WM subsystem working in concert or are unique to the (a) domain-general central

executive that reacts to changing attentional/multi-task demands or (b) primary phonological WM subsystem component processes (i.e., storage and subvocal rehearsal processes). Central executive functioning rather than storage/rehearsal capacity, however, represents the more likely candidate given that the effect of activity level on performance was not confounded by increases in cognitive load (i.e., set size), which reflects storage/rehearsal demands based on Baddeley's (2007) model of WM.

Clinical implications

Collectively, the present findings suggest that poorer phonological WM abilities in children with ADHD are associated with an inability to up-regulate motor activity to facilitate optimal task performance. Investigations that systematically and experimentally manipulate children's activity level through provocation and rarefication paradigms will be needed to confirm the extent to which a facilitative relationship exists among activity level and other key behavioral and classroom functional outcomes (e.g., academic performance, productivity, engagement). The current finding also suggests that existing behavioral treatments that include specific consequences to reduce general activity level (Barkley, 2006; Fabiano et al., 2005; Tryon et al., 2006) may have unintended consequences that impede the phonological WM performance of children with ADHD while working on academic activities that require these central executive processes. Notably, behavioral modification programs may themselves need to be modified to include instructional or environmental allowances that facilitate the modulation of activity level in combination with contingencies that maximize attentive behavior for children with ADHD. Specialized devices and alternative types of seating (e.g., movement balls and seats) that enable higher rates of controlled motor movement without concomitant reductions in attention also merit scrutiny for children with ADHD.

APPENDIX A: IRB APPROVAL

Approval of Human Research

From: **UCF Institutional Review Board #1**
         FWA00000351, IRB00001138

To: **Mark D. Rapport** and Co-PI: **Valerie K. Sims**

Date: **December 20, 2012**

Dear Researcher:

On 12/20/2012, the IRB approved the following human participant research until 12/19/2013 inclusive:

Type of Review:	IRB Continuing Review Application Form
Project Title:	Attention Deficit/Hyperactivity Disorder (ADHD): The Role of Working Memory as a Core Deficit
Investigator:	Mark D Rapport
IRB Number:	SBE-07-04348
Funding Agency:	
Grant Title:	
Research ID:	n/a

The Continuing Review Application must be submitted 30days prior to the expiration date for studies that were previously expedited, and 60 days prior to the expiration date for research that was previously reviewed at a convened meeting. Do not make changes to the study (i.e., protocol, methodology, consent form, personnel, site, etc.) before obtaining IRB approval. A Modification Form **cannot** be used to extend the approval period of a study. All forms may be completed and submitted online at https://iris.research.ucf.edu .

If continuing review approval is not granted before the expiration date of 12/19/2013, approval of this research expires on that date. When you have completed your research, please submit a Study Closure request in iRIS so that IRB records will be accurate.

Use of the approved, stamped consent document(s) is required. The new form supersedes all previous versions, which are now invalid for further use. Only approved investigators (or other approved key study personnel) may solicit consent for research participation. Participants or their representatives must receive a copy of the consent form(s).

In the conduct of this research, you are responsible to follow the requirements of the Investigator Manual.

On behalf of Sophia Dziegielewski, Ph.D., L.C.S.W., UCF IRB Chair, this letter is signed by:

Signature applied by Joanne Muratori on 12/20/2012 02:53:56 PM EST

IRB Coordinator

APPENDIX B: TABLES

Table 1. Sample and Demographic Variables

Variable	ADHD		TD		
	M	*SD*	*M*	*SD*	*F* (1, 50)
Age	9.22	1.05	10.18	1.31	8.53**
FSIQ	104.83	12.54	108.83	11.51	1.40
SES	48.79	11.70	52.91	10.19	1.78
AD/HD Problems					
CBCL	71.86	7.58	54.17	7.54	70.24***
TRF	66.41	7.28	53.50	4.82	51.88***
ADHD Symptom Severity					
CSI-Parent	78.14	9.53	49.17	11.48	98.89***
CSI-Teacher	65.31	14.76	48.73	7.61	23.04***

Note: ADHD = children diagnosed with attention-deficit/hyperactivity disorder; CBCL = Child Behavior Checklist *T*-scores; CSI = Child Symptom Inventory severity *T*-scores; FSIQ = Full Scale Intelligence Quotient; SES = socioeconomic status; TD = typically developing children; TRF = Teacher Report Form.
** $p \leq .01$, *** $p \leq .001$

Table 2. Phonological working memory performance (% stimuli correct per trial) as a function of diagnostic group and increasing activity level

| | Activity Level Condition | | | | | | |
| | **1** | **2** | **3** | **4** | **Group Composite** | | |
	M (SD)	*M (SD)*	*M (SD)*	*M (SD)*	*M (SE)*	*F*	Set Size Contrasts
ADHD	63.77(25.63)	54.68 (25.21)	66.23 (21.96)	76.80 (17.29)	65.37 (2.11)	5.25**	4>1=2=3
TD	89.74(10.05)	85.05 (14.79)	76.99 (19.32)	82.67 (15.23)	83.61 (2.37)	3.02*	3>1=2=4; 3=2; 3=4
Activity Level Composite	75.26 (23.96)	68.11 (25.99)	70.99 (21.32)	79.39 (16.51)	--	3.04*	
Group *F*	20.99***	26.17***	3.41	0.21	32.99***		
Group Contrasts	TD > ADHD	TD > ADHD			TD > ADHD		

Note: ADHD = children diagnosed with attention-deficit/hyperactivity disorder; SD = standard deviation; SE = standard error; TD = typically developing children.

* $p < .05$; ** $p \leq .01$; *** $p \leq .001$

[a] Phonological performance group x activity level interaction, $F (5,150) = 5.08$, $p < .005$

Table 3. Attentive behavior (% of task oriented) as a function of diagnostic group and increasing activity level

	Activity Level Condition				Group Composite	
	1	**2**	**3**	**4**		
	M (SD)	*M (SD)*	*M (SD)*	*M (SD)*	*M (SE)*	*F*
ADHD	77.68 (19.73)	71.65 (21.53)	71.77 (24.81)	79.38 (21.61)		
TD	97.31 (4.73)	96.44 (4.81)	90.78 (10.38)	93.29 (7.87)		
Activity Level Composite	86.36 (17.90)	82.62 (20.47)	80.18 (21.80)	79.38 (21.61)	--	
Group x Activity Level	21.70***	29.23***	11.81***	8.6**		2.09
Group Contrasts	TD > ADHD	TD > ADHD	TD > ADHD	TD > ADHD	TD > ADHD	

Note: ADHD = children diagnosed with attention-deficit/hyperactivity disorder; SD = standard deviation; SE = standard error; TD = typically developing children.
** $p \leq .01$; *** $p \leq .001$

Table 4. Percentage of task children exhibited overall and individual movement categories as a function of group and activity level

	Activity Level Condition							
	1		**2**		**3**		**4**	
	ADHD	TD	ADHD	TD	ADHD	TD	ADHD	TD
	M (SD)	*M (SD)*	*M (SD)*	*M (SD)*	*M (SD)*	*M (SD)*	*M (SD)*	*M (SD)*
Overall Activity Level	60.77 (19.70)	43.30 (25.95)	72.87 (19.57)	57.49 (25.35)	81.13 (12.14)	67.44 (23.82)	89.09 (9.96)	78.54 (20.11)
Movement Type								
Auxiliary Chair	2.76 (3.98)	0.55 (1.48)	6.02 (7.04)	0.58 (1.11)	5.73 (7.33)	1.28 (2.10)	6.47 (12.47)	1.41 (2.79)
Chair Spinning	3.23 (8.43)	0.00 (0.00)	3.62 (6.77)	0.43 (2.06)	6.31 (10.17)	0.05 (0.25)	5.63 (9.60)	2.31 (8.22)
Chair Swinging	32.04 (18.06)	28.72 (28.50)	38.71 (16.75)	42.81 (27.05)	43.77 (21.85)	48.65 (22.61)	57.26 (23.35)	55.17 (26.53)
Foot Movement	60.96 (19.65)	42.24 (27.21)	72.81 (19.53)	57.53 (25.36)	81.09 (12.14)	67.45 (23.82)	88.00 (12.54)	78.52 (20.08)
Out of Chair	7.71 (20.95)	0.03 (0.09)	4.78 (9.81)	0.18 (0.42)	4.38 (11.26)	0.16 (0.48)	3.04 (8.62)	4.39 (20.84)

Note: ADHD = children diagnosed with attention-deficit/hyperactivity disorder; SD = standard deviation; SD = standard deviation; TD = typically developing children.

APPENDIX C: FIGURES

Phonological Task

| 6 | 2 | M | 5 | Verbal Response: 2, 5, 6, M |

Correct Response Sequence
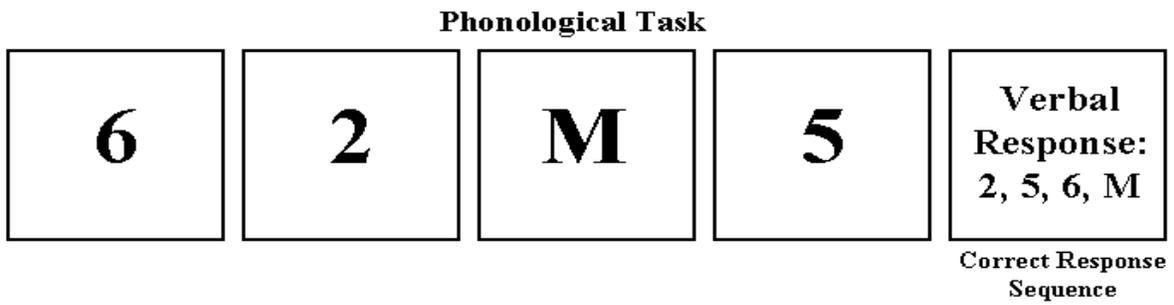
Figure 1. Visual schematic of the phonological working memory task
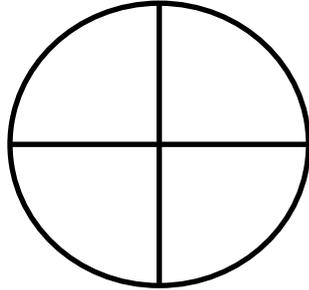
Figure 2. Visual schematic depicting imagined stationary axes extending from the child to the computer monitor and 90 degrees left and right of the child that was used to code chair movement.
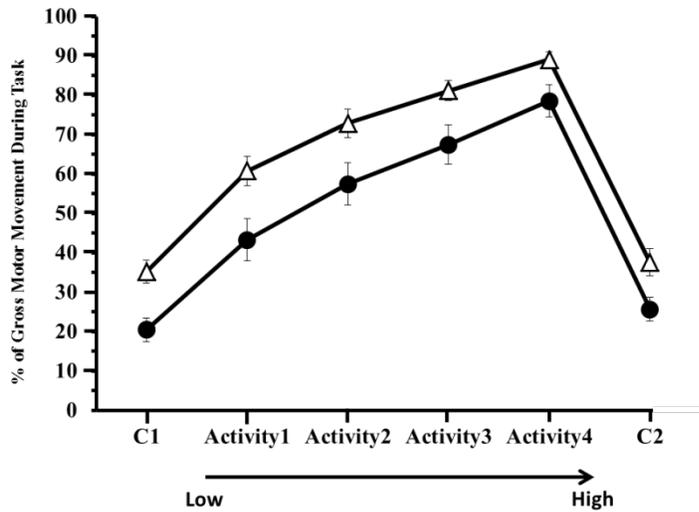
Figure 3. Validation of activity level differences during the phonological working memory task relative to pre- and post-control conditions. Note: ADHD = attention-deficit/hyperactivity disorder; C1 = control condition (pre); C2 = control condition (post). Error bars represent standard error. Closed circles represent typically developing children. Open triangles represent children with attention-deficit/hyperactivity disorder.
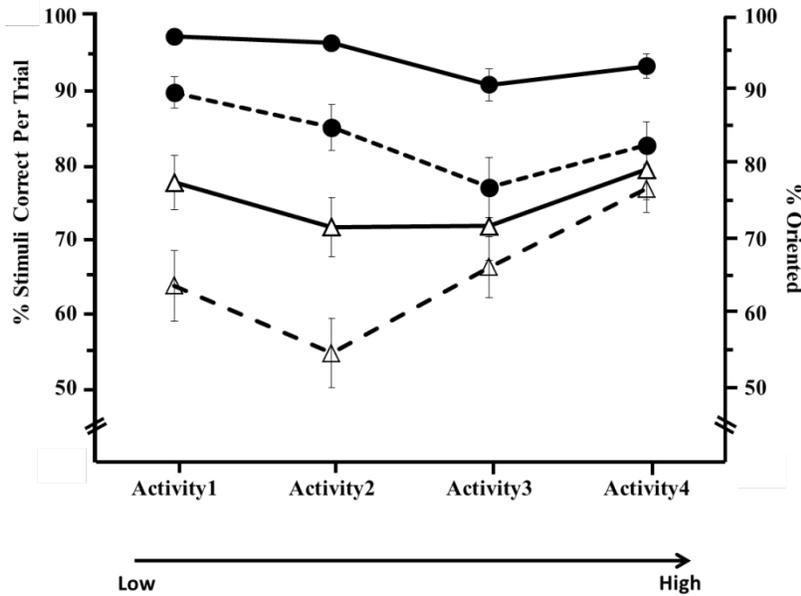
Figure 4. Effects of increasing activity level on phonological working memory performance (percent of stimuli correct per trial) and attentive behavior (percent of task oriented). ADHD = attention-deficit/hyperactivity disorder; TD = typically developing. Closed circles represent typically developing children. Open triangles represent children with attention-deficit/hyperactivity disorder. Dashed lines represent percent of stimuli correct per trial (left ordinate); solid lines represent attentive behavior (right ordinate).

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