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Adhd And Working Memory: The Impact Of Central Executive Deficits And Overwhelming Storage/rehearsal Capacity On Observed Inattentive Behavior

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ADHD AND WORKING MEMORY: THE IMPACT OF CENTRAL EXECUTIVE DEFICITS AND OVERWHELMING STORAGE/REHEARSAL CAPACITY ON OBSERVED INATTENTIVE BEHAVIOR

by

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ABSTRACT

Inattentive behavior is considered a core and pervasive feature of ADHD; however, an alternative model challenges this premise and hypothesizes a functional relationship between working memory and inattentive behavior. The current study investigated whether inattentive behavior in children with ADHD is functionally related to domain-general central executive and/or subsidiary storage/rehearsal components of working memory. Objective observations of children's attentive behavior by independent observers were conducted while children with ADHD (n=15) and typically developing children (n=14) completed 10 counterbalanced tasks that differentially manipulated central executive, phonological storage/rehearsal, and visuospatial storage/rehearsal demands. Results of latent variable and effect size confidence interval analyses revealed two conditions that completely accounted for the attentive behavior deficits in children with ADHD: (a) placing demands on central executive processing, the effect of which is evident under even low cognitive loads, and (b) overwhelming storage/rehearsal capacity, which has similar effects on children with ADHD and typically developing children but occurs at lower cognitive loads for children with ADHD. Collectively, the results challenge the current DSM-IV conceptualization of ADHD and indicate that inattentive behavior may be secondary to underlying working memory deficits.

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LIST OF ACRONYMS

A/B	At or Below Working Memory Span
ADHD	Attention-Deficit/Hyperactivity Disorder
C	Control condition
CBCL	Child Behavior Checklist
CE	Central Executive
CLC-IV	Children's Learning Clinic – IV
CSI	Child Symptom Inventory
DSM-IV	Diagnostic and Statistical Manual of Mental Disorders – IV
FSIQ	Full Scale Intelligence Quotient
K-SADS	Kiddie Schedule for Affective Disorders and Schizophrenia for School-Aged Children
ODD	Oppositional Defiant Disorder
PH	Phonological
SES	Socioeconomic Status
TD	Typically Developing
TRF	Teacher Report Form
VS	Visuospatial
WISC	Wechsler Intelligence Scale for Children
WM	Working Memory

CHAPTER 1: INTRODUCTION

Recent meta-analytic (Martinussen, Hayden, Hogg-Johnson, & Tannock, 2005; Willcutt, Doyle, Nigg, Faraone, & Pennington, 2005) and experimental (Brocki, Randall, Bohlin, & Kerns, 2008; Martinussen & Tannock, 2006; Marzocchi et al., 2008; Rapport, Alderson et al., 2008; Roodenrys, Koloski, & Grainger, 2001) studies are highly consistent in documenting working memory impairments in children with attention-deficit/hyperactivity disorder (ADHD) relative to typically developing children. Working memory is a limited capacity system that temporarily stores and processes information for use in guiding behavior (Baddeley, 2007). Its three primary components include a domain-general central executive, and two subsystems for the temporary storage and rehearsal of modality-specific phonological and visuospatial information. The central executive is an attentional controller responsible for oversight and coordination of the subsidiary systems. Its primary functions are focusing attention, dividing attention among concurrent tasks, and providing an interface between working memory and long-term memory. The phonological subsystem is responsible for the temporary storage and rehearsal of verbal material, whereas the visuospatial subsystem provides this function for non-verbal visual and spatial information. A fourth component – the episodic buffer – has been hypothesized recently as a mechanism to integrate verbal and visuospatial information, but awaits empirical scrutiny. Extensive neuropsychological (Baddeley, 2003), neuroanatomical (Smith, Jonides, & Koeppe, 1996), neuroimaging (Fassbender & Schweitzer, 2006), and factor analytic (Alloway, Gathercole, & Pickering, 2006) investigations support the distinct functioning of the two subsystems, their storage and rehearsal components, and the domain-general central executive.

Identifying deficits in specific working memory components is useful because of the unique contributions that each component makes to academic processes and outcomes. For example, the central executive is implicated in general fluid intelligence (Kane et al., 2004; Miyake, Friedman, Rettinger, Shah, & Hegarty, 2001) vocabulary, literacy, and arithmetic (Gathercole & Pickering, 2000; Swanson & Kim, 2007), reading comprehension (Swanson & Howell, 2001), verbal and quantitative achievement (Engle, Tuholski, Laughlin, & Conway, 1999), and lexical-semantic/orthographic abilities (Larigauderie, Gaonac'h, & Lacroix, 1998; van Daal, Verhoeven, van Leeuwe, & van Balkom, 2008). Visuospatial storage/rehearsal is involved in visual reasoning (Kane et al., 2004) and speech production abilities (van Daal et al., 2008), whereas phonological storage/rehearsal is necessary for verbal reasoning (Kane et al., 2004), vocabulary (Gathercole & Pickering, 2000), word recognition (Swanson & Howell, 2001), verbal achievement (Engle et al., 1999), arithmetic (Swanson & Kim, 2007), and phonological and syntactic abilities (Larigauderie et al., 1998; van Daal et al., 2008).

The question of whether deficiencies in specific underlying mechanisms or processes are unique to a particular disorder such as ADHD is central to the utility of child psychopathology theory development. Recent studies have begun to address this question with respect to the functional working memory model of ADHD (Rapport, Chung, Shore, & Isaacs, 2001; Rapport, Kofler, Alderson, & Raiker, 2008). Converging evidence indicates that children with ADHD are impaired in all three components of working memory, with the largest deficits found in the domain-general central executive (CE) system, followed by visuospatial (VS) storage/rehearsal and then phonological (PH) storage/rehearsal subsystems (i.e., deficits in CE > VS > PH; Marzocchi et al., 2008; Rapport, Alderson et al., 2008; Martinussen et al., 2005; Willcutt et al., 2005). The central executive component of working memory also is related functionally to the excess motor activity (i.e., hyperactivity) that is a hallmark and key diagnostic feature of ADHD (Rapport et al., 2009).

ADHD-related working memory deficits have been linked recently with classroom inattention, which in turn is a primary catalyst for clinical referrals (Pelham, Fabiano, & Massetti, 2005). Significant correlations between laboratory measures of working memory and teacher ratings of classroom inattention are usually (Aronen, Vuontela, Steenari, Salmi, & Carlson, 2005; Lee, Riccio, & Hynd, 2004; Martinussen & Tannock, 2006; Savage, Cornish, Manly, & Hollis, 2006; Thorell, 2007) but not always reported (Rucklidge & Tannock, 2002), and range from -.20 to -.46 across studies. Correlating laboratory-based working memory performance with teacher ratings of inattention, however, may underestimate the magnitude of the relationship. Working memory tasks in the laboratory typically require 5-15 minutes to complete. In contrast, teacher ratings reflect subjective, global endorsements of children's behavior over time intervals ranging from the past week to the preceding six months, and activities that vary with respect to working memory demands. Moreover, teacher rating scale scores used to quantify children's inattention yield limited information regarding processes or mechanisms potentially responsible for the relationship between working memory and inattention. They are susceptible also to several potential sources of error associated with retrospective recall, halo effects, and rater expectation bias (Harris & Lahey, 1982; Kofler, Rapport, & Alderson, 2008).

The link between working memory and attentive behavior – the antithesis of classroom inattention – has been examined in several unique and diverse contexts. Observational studies, for example, reveal that children are more likely to abandon tasks that exceed their individual working memory capacities (Gathercole & Alloway, 2008). Kane and colleagues (Kane, Brown et al., 2007) provide further experimental evidence for a link between working memory and attentive behavior. In a novel, naturalistic study, they concluded that individuals with low working memory abilities were significantly more likely to report task-unrelated thoughts (i.e., inattention), especially during challenging or difficult tasks throughout the day.

The domain-general central executive component of Baddeley's (2007) working memory model is a particularly appealing candidate to explain observed attentive behavior deficits in children with ADHD for several reasons: (a) it has been shown to be the most impaired working memory component in ADHD (Rapport, Alderson et al., 2008); (b) it has been linked experimentally with hyperactivity (Rapport et al., 2009); and (c) a primary function of the central executive is the control and focus of attention (Baddeley, 2007). Twenty-five years of experimental research specifically investigating potential cognitive processes associated with central executive functioning, however, has failed to reliably demonstrate ADHD-related impairments in focused (Sharma, Halperin, Newcorn, & Wolf, 1991; van der Meere & Sergeant, 1988) and selective attention (Huang-Pollock, Carr, & Nigg, 2002; Huang-Pollock, Nigg, & Carr, 2005; Lajoie et al., 2005; Sergeant & Scholten, 1983; Tarnowski, Prinz, & Nay, 1986). Moreover, empirical studies have demonstrated a normal (van der Meere & Sergeant, 1987) or unimpairing (van Mourik, Oosterlaan, Heslenfeld, Konig, & Sergeant, 2007) response to distractions, and intact visual orienting processes in children with ADHD (Huang-Pollock & Nigg, 2003). Studies of divided attention are equivocal, with some studies reporting superior (Koschack, Kunert, Derichs, Weniger, & Irle, 2003), similar (Lajoie et al., 2005; van der Meere & Sergeant, 1987), or impaired (Karatekin, 2004; Tucha et al., 2006) divided attention abilities in children with ADHD relative to typically developing children.

The failure to find a reliable relationship between deficient central executive working memory processes and inattentiveness may be due to at least two factors. Previous studies of focused attention in children with ADHD have concentrated on examining the focus of *visual attention* to externally presented stimuli. Successful performance on these recognition paradigms does not require a specific selection mechanism *within* working memory because the information is present in the environment (Cabeza et al., 1997; Kahana, Rizzuto, & Schneider, 2005; MacLeod & Kampe, 1996). An *internal* focus of attention (one of the three central executive processes) is needed, however, when the required information must be retrieved from memory and processed while minimizing potential internal and external interference effects (Garavan, 1998; Oberauer, 2003). If this mechanism contributes significantly to children's inattentiveness, decreases in attention would be observed even under low working memory conditions (i.e., without overwhelming the storage/rehearsal subsystems).

An alternative possibility is that the inattentive behavior observed in children with ADHD during academic and other activities involving working memory is a function of task demands that overwhelm the limited capacity of one or both storage/rehearsal components. In general, children with poor working memory are more likely to abandon tasks or "zone out" (p. 71) as the quantity of information to be recalled increases (i.e., as demands on phonological and/or visuospatial storage/rehearsal increase; Gathercole & Alloway, 2008). No study to date, however, has objectively measured attentive behavior while concurrently, experimentally manipulating demands on the visuospatial/phonological storage/rehearsal components to determine whether overwhelming working memory subsystem processes adversely affects observed attentive behavior.

The current study uses a total of 10 task conditions: (a) pre- and post-test control conditions that place minimal demands on the central executive and subsystem storage/rehearsal processes; (b) four phonological working memory conditions of increasing memory load (i.e., increasing the number of stimuli to be mentally manipulated and recalled); and (c) four visuospatial working memory conditions of increasing memory load. According to Baddeley (2007), central executive demands increase from control to working memory conditions, and remain stable across memory loads (i.e., increasing only the number of stimuli to be manipulated and recalled does not increase demands on the central executive). Conversely, demands on storage/rehearsal processes increase from control to working memory conditions, and increase incrementally under heavier memory load conditions. As a result, if attentive behavior deficits in ADHD are primarily related to central executive dysfunction (i.e., focus of attention within working memory), observed rates of attentive behavior should decrease significantly from control to working memory conditions, and remain stable across increasing phonological and visuospatial memory load conditions. Conversely, if ADHD-related attentive behavior deficits are primarily related to modality-specific (phonological, visuospatial) storage/rehearsal deficiencies, systematically increasing memory load on these components should correspond with incremental decreases in attentive behavior. In addition, significant differences should be apparent when one exceeds the child's working memory span. A third possibility – hypothesized in the current study – is that attentive behavior deficits are related to both impaired central executive and storage/rehearsal processes. In this case, attentive behavior is expected to decrease initially due to impaired attentional focus needed to process stored stimuli (Oberauer, 2003), and decrease again when task demands exceed children's working memory capacity. Finally, if attention deficits are a ubiquitous feature of the disorder or unrelated to working memory, similar rates of

ADHD-related inattentive behavior should be observed across control and working memory conditions.

CHAPTER 2: METHODOLOGY

Participants

The sample was comprised of 29 boys aged 8 to 12 years (*M* = 9.73, *SD* = 1.36), recruited by or referred to the Children's Learning Clinic (CLC-IV) through community resources (e.g., pediatricians, community mental health clinics, school system personnel, self-referral). The CLC-IV 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 agreed 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. All parents and children gave their informed consent/assent to participate in the study, and 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). 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 interrater 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).

Fifteen children met the following criteria and were included in the ADHD-Combined Type group: (1) an independent diagnosis by the CLC-IV's directing clinical psychologist using DSM-IV criteria for ADHD-Combined Type based on K-SADS interview with parent and child which assesses symptom presence and severity across home and school settings; (2) parent ratings of at least 2 *SD*s above the mean on the Attention-Deficit/Hyperactivity Problems DSM-Oriented 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, 2004); and (3) teacher ratings of at least 2 *SD*s above the mean on the Attention-Deficit/Hyperactivity Problems DSM-Oriented 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. Their psychometric properties are well established (Rapport, Kofler et al., 2008). All children in the ADHD group met criteria for ADHD-Combined Type, and six were comorbid for Oppositional Defiant Disorder (ODD).

Fourteen 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 all CBCL[1] and TRF scales; and (4) parent and teacher ratings within the non-clinical range on all CSI subscales. Typically developing children were actively recruited through contact with neighborhood and community schools, family friends of referred children, and other community resources.

Children 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. None of the children were receiving medication during the study – eight of the children with ADHD had previously received trials of psychostimulant medication. Demographic and rating scale data for the two groups are provided in Table 1.

Measures

Visual attention to task.

Direct observations of attentive behavior while children completed working memory tasks were used in the current study predicated on previous research indicating that laboratory observations of attentive behavior predict classroom attention (r = .38 to .53) better than traditional laboratory measures of attention such as continuous performance tests (Weis & Totten, 2004). A ceiling-mounted digital video camera was used to record children's behavior while they completed each of the tasks described below. MPEG-4 video files were created for each testing session. For each child, two observers used the Noldus Observational System (2003) computer software to independently code behavior into one of two mutually exclusive states. Participants were coded as *oriented* to task if their head was directed within 45° vertically/horizontally of the center of the monitor. Participants looking at the keyboard during

[1] One typically developing child had a primary sleep disorder resolved with melatonin, and another has elevated

the response phase of the visuospatial task were coded as *oriented*. They were coded as *not oriented* to task if their head direction exceeded 45° vertical/horizontal tilt for more than two consecutive seconds. Behavior was coded using a continuous observation scheme. 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). The term oriented was used *in lieu* of the traditional on-task moniker to remind coders to code the observed behavior, not the assumed underlying intention (Harris & Lahey, 1982). Research assistants were trained extensively and required to obtain a minimum percent agreement of .80 compared to a gold standard practice tape as a prerequisite to coding participants. Intermittent group trainings were held to minimize observer drift. Interrater reliability was tested for all observation days. Tapes that initially did not meet the minimum acceptable percent agreement of 80% were recoded following a meeting between both coders and a doctoral-level research assistant during which behavioral definitions were reviewed and specific disagreements were viewed and discussed. Interrater reliability was rechecked following independent recoding and the process was repeated until satisfactory interrater reliability was achieved. Overall percent agreement across all tapes was .94, with a kappa of .88.

Phonological (PH) working memory task

The phonological working memory task is similar to the Letter-Number Sequencing subtest on the WISC-IV (Wechsler, 2003), and assesses phonological working memory based on Baddeley’s (2007) model. Children were presented a series of jumbled numbers and a capital letter on a computer monitor (Figure 1). Each 4 cm height by 2 cm width number and letter appeared on the screen for 800 ms, followed by a 200 ms interstimulus 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). Two trained research assistants, shielded from the participant's view, listened to the children's vocalizations through headphones in a separate room and independently recorded oral responses (interrater reliability = 95.8% agreement).

Visuospatial (VS) working memory task

Children were shown nine 3.2 cm squares arranged in three vertical columns on a computer monitor (Figure 1). The columns were offset from a standard 3x3 grid to minimize the likelihood of phonological coding of the stimuli (e.g., by equating the squares to numbers on a telephone pad). A series of 2.5 cm diameter dots (3, 4, 5, or 6) were presented sequentially in one of the nine squares during each trial, such that no two dots appeared in the same square on a given trial. All but one dot presented within the squares was black – the exception being a red dot that was counterbalanced across trials to appear an equal number of times in each of the nine squares, but never presented as the first or last stimulus in the sequence to minimize potential primacy and recency effects. Each dot was displayed for 800 ms followed by a 200 ms interstimulus interval. A green light appeared at the conclusion of each 3, 4, 5, and 6 stimuli sequence. Children were instructed to indicate the serial position of black dots in the order presented by pressing the corresponding squares on a computer keyboard, and to indicate the position of the red dot last. The last response was followed by an intertrial interval of 1000 ms and an auditory chime that signaled the onset of a new trial.

Control (C) conditions

Children's attentive behavior was assessed while they used the Microsoft® Paint program for five consecutive minutes both prior to (C1) and after (C2) completing the phonological and visuospatial working memory tasks during four consecutive Saturday assessment sessions. The Paint program served as pre and post conditions to assess and control for potential within-day fluctuations in attentive behavior (e.g., fatigue effects). Children sat in the same chair and interacted with the same computer used for the working memory tasks while interacting with a program that placed minimal demands on working memory (i.e., the Paint program allows children to draw/paint anything they like on the monitor using a variety of interactive tools[2]). Attentive behavior during the four pre and four post control conditions was averaged separately to create pre and post composite scores secondary to preliminary analyses that found no differences in children's pre or post condition attentive behavior across days (all $p > .25$).

Measured intelligence

All children were administered either the Wechsler Intelligence Scale for Children third or fourth edition to obtain an overall estimate of intellectual functioning. 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. Full Scale IQ (FSIQ) was not analyzed as a covariate for conceptual reasons. IQ and working memory share significant variance (latent variable correlations of .47 to .90 across experimental and meta-analytic investigations; Ackerman, Beier, & Boyle, 2005; Colom, Abad, Rebollo, & Shih, 2005; Engle et al., 1999).

[2] Interaction with the Paint program places minimal demands on central executive processes (e.g., focused attention, interaction with long-term memory) and phonological and visuospatial storage/rehearsal processes.

Using FSIQ as a covariate would therefore result in removing substantial variance associated with working memory from working memory. A residual FSIQ score was derived using a latent variable approach to correct for this problem. Briefly, the derived central executive, phonological storage/rehearsal, and visuospatial storage/rehearsal performance variables described below were covaried out of FSIQ (R^2 = .33, p = .02). Residual FSIQ scores represent IQ that is unrelated to estimated WM functioning, and were examined as a potential covariate in the analyses described below.

Procedures

The phonological and visuospatial tasks were programmed using SuperLab Pro 2.0 (2002). All children participated in four consecutive Saturday assessment sessions at the CLC-IV. The phonological, visuospatial, and control conditions were administered as part of a larger battery of laboratory-based tasks that required the child's presence for approximately 2.5 hours per session. Children completed all tasks while seated alone in an assessment room. All children received brief (2-3 min) breaks following every task, and preset longer (10-15 min) breaks after every two to three tasks to minimize fatigue. Each child was administered eight control (pre and post on each of the four days), four phonological, and four visuospatial conditions (i.e., PH and VS set sizes 3, 4, 5, and 6) across the four testing sessions. Each phonological and visuospatial set size consisted of 24 trials. Details concerning the administration of practice blocks for the visuospatial and phonological paradigms are described in Rapport, Alderson et al. (2008). The eight working memory conditions were counterbalanced to control for order effects. The control conditions always occurred as the first and last tasks each day. Children were seated in a caster-wheel swivel chair approximately 0.66 meters from the computer monitor for all tasks.

Dependent variables

Attentive behavior (percent oriented) refers to the percentage of time during each of the 10 tasks (C1, VS and PH set sizes 3, 4, 5, and 6, and C2) that children were visually attending to the task. Performance data (stimuli incorrect per trial) were computed and used to statistically isolate the relationship between observed attentive behavior and specific components of working memory.

Statistical Analysis

A 4-tier analytic approach was used to examine (a) potential overall between-group differences in observed attentive behavior among working memory systems (phonological, visuospatial); (b) group differences and changes in attentive behavior associated with phonological and visuospatial working memory demands; (c) the extent to which attentive behavior is directly related to individual working memory component processes, and whether this relationship differs between children with ADHD and typically developing children; and (d) whether observed attentive behavior deficits are a ubiquitous feature of ADHD or a byproduct of working memory deficits. Measurement of attentive behavior while children performed working memory tasks allowed direct examination of the relationship between working memory and attentive behavior. Latent variable (cf. Swanson & Kim, 2007) and performance-based supplementary analyses were used to (a) confirm the relationships among the independent (working memory components) and dependent (observed attention) variables, (b) estimate the magnitude of these relationships, and (c) statistically estimate the relative contribution of central executive and storage/rehearsal processes to changes in observed attentive behavior across conditions.

CHAPTER 3: RESULTS

Data Screening

Power Analysis

An average Hedges' *g* effect size (ES) of 1.40 was obtained in the recent meta-analytic review of observed classroom inattentive behavior in children with ADHD relative to typically developing children (Kofler et al., 2008). GPower software version 3.0.5 (Faul, Erdfelder, Lang, & Buchner, 2007) was used to determine needed sample size using this ES, with power set to .80 as recommended by Cohen (1992). For an ES of 1.40, $\alpha = .05$, power $(1 - \beta) = .80$, 2 groups, and 6 repetitions (C1, set sizes 3-6, C2 as described below), 12 total participants are needed for a repeated measures ANOVA to detect differences and reliably reject $H_{\varnothing}$. Twenty-nine children participated in the current study.

Missing data, outliers, and multicollinearity

Recommendations by Tabachnick and Fidell (2007) and Kline (2005) were adopted for all data screening and cleaning operations. Three data points (one for each of three subjects) were estimated using group mean substitution. Each of the 10 tasks (C1, PH set sizes 3-6, VS set sizes 3-6, C2) were screened for univariate and multivariate outliers and tested against $p < .001$. A value equal to one smaller than the next most extreme score was substituted for one subject's post baseline and one subject's visuospatial set size 6 score. No multivariate outliers (Mahalanobis distance) or multicollinear variables (all tolerance > .10; all variance inflation factors < 10) were identified.

Preliminary Analyses

Sample ethnicity was mixed with 18 Caucasian (62%), 7 Hispanic (24%), 2 African American (7%), and 2 multiracial children (7%). 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 differed on intelligence (WISC-III or WISC-IV FSIQ), $t(27) = 2.22$, $p = .04$, age, $t(27) = 2.26$, $p = .03$, and SES, $t(27) = 2.15$, $p = .04$. In general, children with ADHD were slightly younger and had lower SES scores relative to typically developing children (Table 1). Age and SES were not significant covariates of any of the Tier I, II, III, or IV analyses (all $p \geq .11$). Residual FSIQ (intelligence unrelated to working memory; see *Measured Intelligence*) did not differ between groups, $t(27) = 0.10$, $p = .92$. We therefore report simple model results with no covariates.

Tier I: Composite Scores

The initial analysis examined overall differences in attentive behavior between working memory modalities (PH, VS) and groups (ADHD, TD). Results are depicted in Tables 2 and 3. Phonological and visuospatial composite scores were computed separately by averaging attentive behavior across set sizes. A Mixed-model ANOVA indicated significant main effects for working memory modality and group (both $p < .0005$). Across groups, children were significantly more attentive during the visuospatial relative to the phonological task; children with ADHD were significantly less attentive than TD children across tasks. The modality by group interaction was not significant ($p = .07$).

Tier II: Set sizes

The second set of analyses examined the effects of increasing phonological and visuospatial memory load on children's attentive behavior (see Tables 2 and 3). Using Wilks' criterion, a significant one-way MANOVA on all 10 conditions (C1, set sizes 3-6 for both modalities, C2) by group (ADHD, TD) confirmed the overall relationship between attentive behavior and working memory, Wilks' $\lambda = 0.27$, $F(10,18) = 4.98$, $p = .002$. Phonological and visuospatial Mixed-model ANOVAs with LSD post hocs were conducted separately to examine group (ADHD, TD) by condition (C1, set sizes 3-6, C2) differences (see Figures 2 and 3 for attentive behavior rates and corresponding performance scores).

Phonological ANOVA

The Mixed-model ANOVA was significant for group, set size, and the group by set size interaction (all $p < .0005$) for attentive behavior during the phonological and control conditions (C1, PH set sizes 3-6, C2). LSD post hoc tests for the interaction revealed that children with ADHD were less attentive across all control and phonological set size conditions compared to TD children (all $p \leq .009$). The pattern of attentive behavior as working memory demands increased, however, was appreciably different between groups. Children with ADHD were significantly more attentive during both control conditions relative to set sizes 3 and 4, and were more attentive during set sizes 3 and 4 relative to set sizes 5 and 6 (all $p \leq .02$). No significant differences were observed between set sizes 3 and 4 ($p = .93$), or set sizes 5 and 6 ($p = .75$; ADHD: C1=C2>3=4>5=6). In contrast, the typically developing group decreased slightly from both control conditions to set size 3 before decreasing moderately at set size 6 relative to the control and set size 3 conditions (all $p \leq .05$; TD: C1=C2>3=4=5>6). No differences were observed between the pre and post control conditions for either group (both $p \geq .18$).

Computation of Hedges' *g* indicated that the average magnitude difference in attentive behavior between children with ADHD and TD children during the phonological tasks was 1.55 standard deviation units (*SE* = 0.42). Results are depicted in Table 2 and Figure 2a.

Visuospatial ANOVA

The Mixed-model ANOVA was significant for group, set size, and the group by set size interaction (all $p < .0005$) for attentive behavior during the visuospatial and control conditions (C1, VS set sizes 3-6, C2). LSD post hoc tests for the interaction revealed that children with ADHD exhibited significantly lower rates of attentive behavior across all control and visuospatial conditions relative to TD children (all $p \leq .009$). The pattern of attentive behavior as working memory demands increased, however, was appreciably different between groups. Children with ADHD were significantly more attentive ($p \leq .04$; all other $p \geq .14$) during both control conditions relative to higher memory load conditions (ADHD: C1=C2>3>4=5=6). TD children, on the other hand, were similarly attentive across most conditions (all $p \geq .06$) before decreasing significantly at the highest memory loads ($p \leq .03$; i.e., TDC: C1=C2=3=4=5>6; C1=C2>5). Hedges' *g* effect size indicated that the average magnitude difference in attentive behavior between children with ADHD and TD children during the visuospatial working memory tasks was 1.45 standard deviation units (*SE* = 0.42). Results are depicted in Table 3 and Figure 2b.

<u>Tier III: Components of Working Memory</u>

Latent variable analyses were undertaken to determine the extent to which group differences in attentive behavior reported above were associated with the domain-general central executive relative to the two subsidiary systems (PH or VS storage/rehearsal). Latent variable analysis is currently the best practice for estimating the independent contribution of working memory component processes (cf. Colom et al., 2005; Conway et al., 2005; Swanson & Kim, 2007). Correlations between derived central executive performance scores at each set size, between phonological storage/rehearsal performance scores at each set size, and between visuospatial storage/rehearsal performance scores at each set size were computed separately to test the premise that central executive demands remain constant despite increasing demands on storage/rehearsal processes (Baddeley, 2007). Results revealed that central executive performance was highly correlated across set sizes (r = .76 to .90, all $p < .0005$). Phonological and visuospatial storage/rehearsal variables, in contrast, were moderately correlated with adjacent set size conditions (e.g., set size 3 with 4, 4 with 5, and 5 with 6; r = .41 to .71; all $p < .002$), but not significantly correlated with set size conditions differing by two or more stimuli (all $p > .10$). This pattern of results supports Baddeley's (2007) assertion that central executive demands remain stable and storage/rehearsal demands increase as the number of stimuli to be manipulated and recalled increases. The findings also substantiate the use of the procedure described below.

Performance scores (% of trials correct) were examined to determine each child's working memory span, defined as the maximum set size at which a child responds correctly on at least 50% of trials (Conway et al., 2005). Attentive behavior rates for each child were categorized according to whether they occurred (a) during the minimal working memory control conditions, (b) during set sizes at or below each child's working memory span, or (c) during set sizes exceeding each child's working memory span[3]. A 2 (group: ADHD, TD) by 3 (WM span: control, at/below, exceeding) Mixed-model ANOVA was conducted to determine the relative contribution of central executive and storage/rehearsal processes to decreases in attentive behavior (Figure 3). The Mixed-model ANOVA was significant for group, $F(1,24) = 22.66$, $p < .0005$, working memory span, $F(2,48) = 28.59$, $p < .0005$, and the group by span interaction, $F(2,48) = 7.51$, $p = .001$. Post hoc analyses revealed significant changes from control to at/below working memory span, and from at/below to exceeding working memory span for both groups (all $p \leq .04$). For typically developing children, the average magnitude of attentive behavior change from control to at/below working memory span conditions was 2.61 percentage points, and 8.96 percentage points from at/below to exceeding working memory span conditions. For children with ADHD, on the other hand, the average magnitude of attentive behavior change from control to at/below working memory span conditions was 16.41 percentage points, and 8.93 percentage points from at/below to exceeding working memory span conditions.

Tier IV: Attentive behavior and working memory performance

Latent variable analyses were used in the final tier to assess the extent to which observed group differences in attentive behavior across all conditions represent ubiquitous inattentive behavior in children with ADHD or the influence of working memory demands (Rapport, Kofler et al., 2008). Residual attentive behavior scores for all eight working memory conditions were computed by regressing working memory performance (stimuli incorrect per trial) onto attentive

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[3] Separate analyses were not conducted for the phonological and visuospatial conditions due to power limitations. Specifically, 10 of the 15 children with ADHD were overwhelmed by the lowest visuospatial set size, consistent with previous findings of more severely impaired visuospatial working memory in children with ADHD (Martinussen et al., 2005; Rapport, Alderson et al., 2008). In addition, 3 of the typically developing children were not overwhelmed even by the highest visuospatial condition. Attentive behavior at/below and exceeding each child's working memory span represents an average across modalities and applicable set sizes (ADHD N=14, TD N=12).

behavior rates at each phonological (R^2 range: .28 to .47) and visuospatial (R^2 range: .19 to .43) set size. Conversely, residual performance scores were computed for each set size by regressing attentive behavior onto working memory performance. Phonological and visuospatial 2 (group) by 4 (condition: set sizes 3-6) Mixed-model ANOVAs on the residual attentive behavior scores (i.e., attentive behavior unrelated to working memory performance) were both nonsignificant for group (both $p \geq .09$), condition (both $p = 1.0$), and the group by condition interaction (both $p \geq .28$), with a Hedges' *g* effect size 95% confidence interval that included 0.0. In contrast, phonological and visuospatial Mixed-model ANOVAs on the residual performance scores (i.e., working memory performance after accounting for attentive behavior) remained significant for group (both $p \leq .004$) and the group by set size interaction (both $p \leq .03$). Hedges' *g* effect sizes indicated that the average magnitude performance difference between children with ADHD and typically developing children was 1.34 standard deviation units (*SE* = 0.41), with a 95% confidence interval that did not include 0.0.

A final analysis was conducted to analyze the extent to which Tier I differences in attentive behavior during the control conditions were accounted for by the minimal working memory demands associated with the Paint program (Rapport et al., 2009). Residual scores were computed for both control tasks by simultaneously regressing the CE, phonological storage/rehearsal, and visuospatial storage/rehearsal composite performance variables onto C1 (R^2=.22) and C2 (R^2=.27) attentive behavior to remove variance associated with working memory functioning. A 2 by 2 Mixed-model ANOVA on the residual attentive behavior scores during the pre and post control conditions revealed no significant effects for group, condition, or the group by condition interaction (all $p \geq .56$), with Hedges' *g* effect size 95% confidence intervals that included 0.0.

Collectively, the preceding analyses reveal that group differences in attentive behavior are no longer evident across conditions after controlling for working memory abilities, whereas the working memory performance of children with ADHD remains significantly impaired across modalities after accounting for differences in attentive behavior.

TABLE 1. Sample and demographic variables

Variable	ADHD		Typically Developing		
	Mean	*SD*	Mean	*SD*	*F*
Age	9.22	1.06	10.29	1.46	5.12*
FSIQ	100.93	13.75	111.57	11.93	4.92*
SES	43.80	11.50	52.46	10.15	4.60*
CBCL					
AD/HD Problems	72.47	5.79	56.64	8.87	32.79***
TRF					
AD/HD Problems	65.67	8.62	55.21	5.90	14.30***
CSI-Parent					
ADHD, Combined	76.33	10.72	52.00	13.34	29.49***
CSI-Teacher					
ADHD, Combined	64.00	10.95	51.00	8.45	12.68***

Note: ADHD = attention-deficit/hyperactivity disorder; CBCL = Child Behavior Checklist; CSI = Child Symptom Inventory severity *T*-scores; FSIQ = Full Scale Intelligence Quotient; SES = socioeconomic status; TRF = Teacher Report Form.
* $p \leq .05$, *** $p \leq .001$

TABLE 2. Phonological set size analyses

	Phonological Set Size[1]							F	Set Size Contrasts
	C1	3	4	5	6	C2	Group Composite		
	$\bar{X}$ (*SD*)	$\bar{X}$ (*SD*)	$\bar{X}$ (*SD*)	$\bar{X}$ (*SD*)	$\bar{X}$ (*SD*)	$\bar{X}$ (*SD*)	$\bar{X}$ (*SE*)		
ADHD	95.75 (5.16)	76.95 (19.09)	76.50 (17.94)	59.85 (22.72)	61.35 (19.91)	97.24 (2.26)	77.94 (2.81)	21.08 ***	C1=C2>3=4>5=6
TD	99.68 (0.56)	97.21 (4.55)	94.01 (4.73)	95.08 (6.16)	88.15 (13.30)	99.41 (0.82)	95.59 (0.66)	5.80 ***	C1=C2>3=4=5>6
Set Size Composite	97.65 (4.17)	86.73 (17.26)	84.95 (15.83)	76.86 (24.42)	74.29 (21.59)	98.28 (2.02)	--	24.11 ***	
Group *F*	8.01**	14.94***	12.50***	31.43***	17.89***	11.48**	35.12***		
Group Contrasts	A>TD	A>TD	A>TD	A>TD	A>TD	A>TD	A>TD		
Hedges' *g* Effect Size	0.17[+]	1.39	1.27	2.01	1.52	0.25[+]			

Note: A = ADHD, C = control, TD = typically developing children; [1] Phonological group x set size interaction, F (5,125) = 8.14, p = .001; ** $p \leq .01$; *** $p \leq .001$

[+] Effect size for attentive behavior after accounting for the minimal working memory demands associated with the control conditions, with 95% confidence intervals that include 0.0.

TABLE 3. Visuospatial set size analyses

	Visuospatial Set Size[1]							***F***	**Set Size Contrasts**
	C1	**3**	**4**	**5**	**6**	**C2**	**Group Composite**		
	$\bar{X}$ (*SD*)	$\bar{X}$ (*SD*)	$\bar{X}$ (*SD*)	$\bar{X}$ (*SD*)	$\bar{X}$ (*SD*)	$\bar{X}$ (*SD*)	$\bar{X}$ (*SE*)		
ADHD	95.75 (5.16)	87.89 (12.03)	77.95 (16.64)	72.34 (17.94)	77.63 (20.03)	97.24 (2.26)	84.80 (2.23)	11.08 ***	C1=C2>3>4=5=6
TD	99.68 (0.56)	98.30 (3.08)	98.85 (1.69)	97.93 (1.71)	94.50 (5.88)	99.41 (0.82)	98.11 (0.43)	7.12 ***	C1=C2=3=4=5>6; C1=C2>5
Set Size Composite	97.65 (4.17)	92.92 (10.24)	88.04 (15.90)	84.69 (18.21)	85.78 (17.03)	98.28 (2.02)	--	12.29 ***	
Group *F*	8.01**	9.87**	21.83***	28.18***	9.17**	11.47**	32.09***		
Group Contrasts	A>TD	A>TD	A>TD	A>TD	A>TD	A>TD	A>TD		
Hedges' *g* Effect Size	0.17+	1.13	1.68	1.91	1.09	0.25+			

Note: A = ADHD, C = control, TD = typically developing children; [1] Visuospatial group x set size interaction, F (5,135) = 8.11, $p \leq .001$; ** $p \leq .01$; *** $p \leq .001$

+ Effect size for attentive behavior after accounting for the minimal working memory demands associated with the control conditions, with 95% confidence intervals that include 0.0.

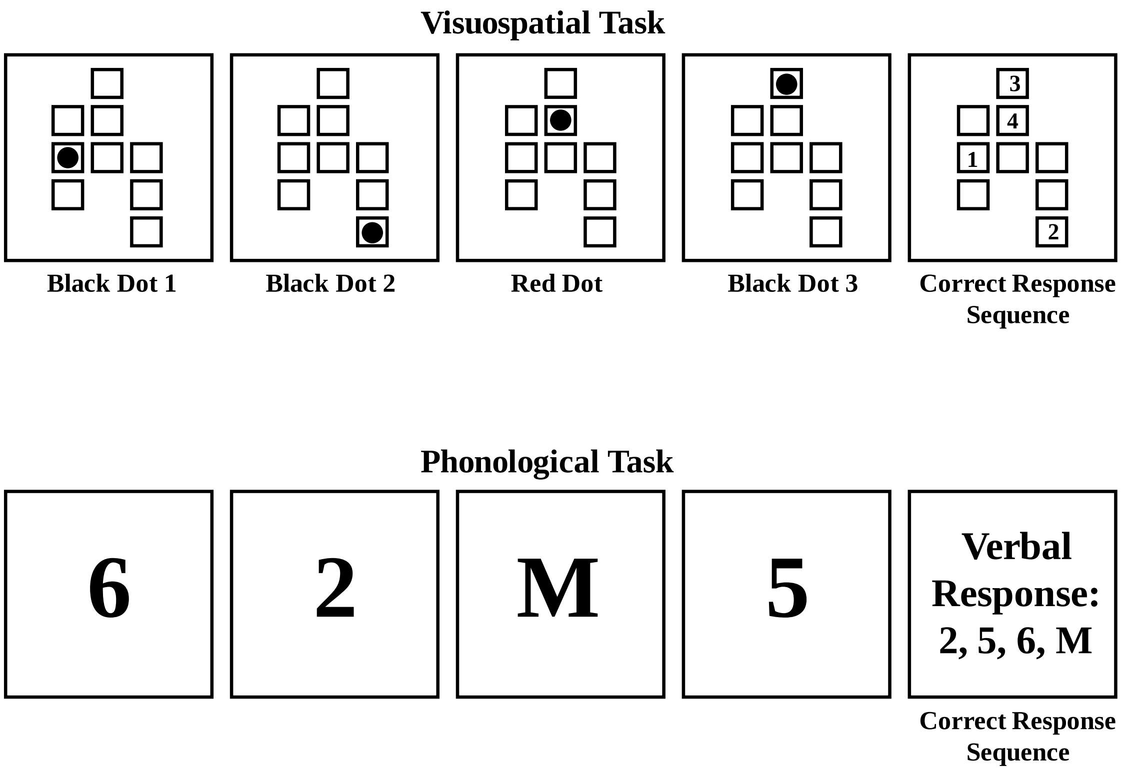
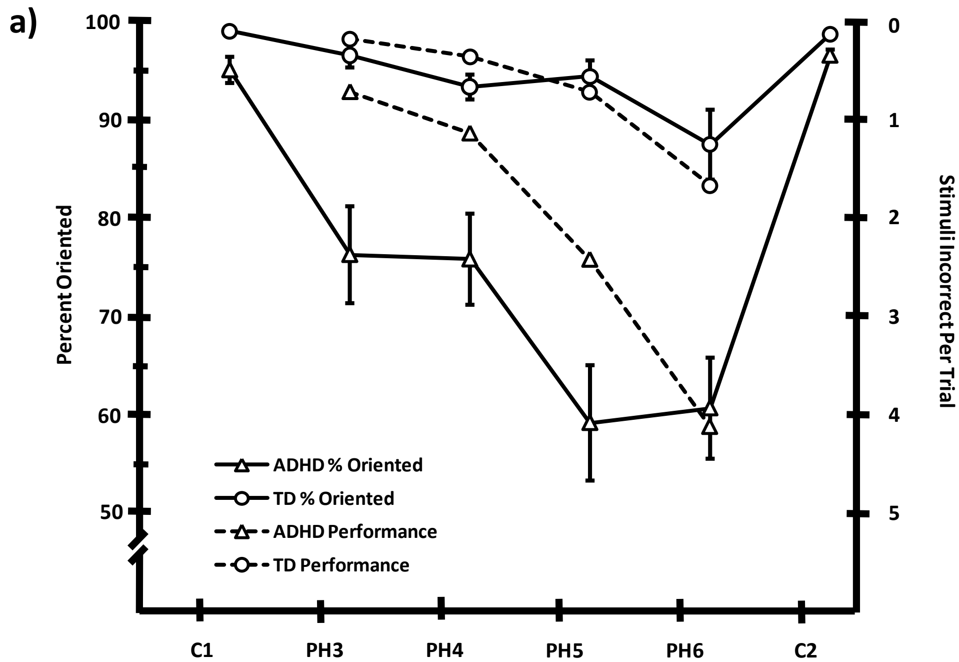


FIGURE 1. Visual schematics of the phonological (top) and visuospatial (bottom) tasks.



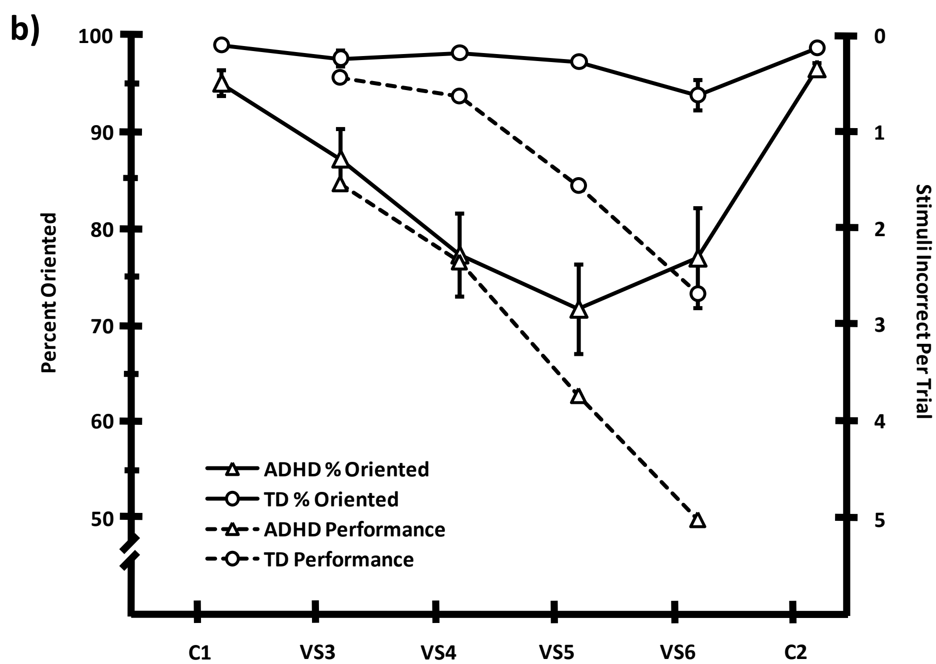


FIGURE 2. Attentive behavior during control and (a) phonological and (b) visuospatial working memory tasks. Solid lines represent attentive behavior (left ordinate); dashed lines represent stimuli incorrect per trial (right ordinate). Error bars reflect *standard error*. ADHD = attention-deficit/hyperactivity disorder; TD = typically developing.

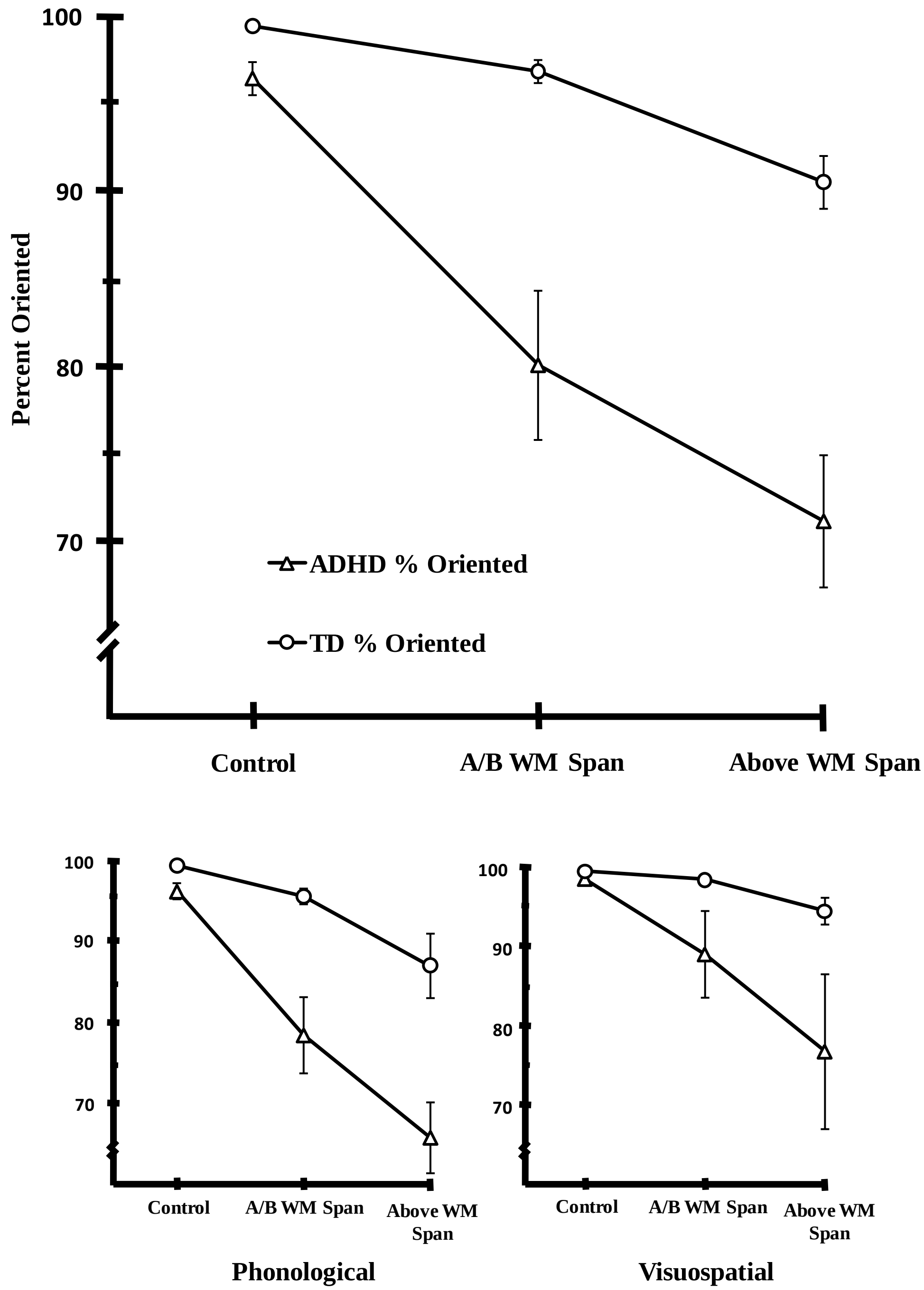


FIGURE 3. Attentive behavior during control conditions and conditions at/below and exceeding each child's working memory capacity. A/B = At/below working memory span; ADHD = attention-deficit/hyperactivity disorder; TD = typically developing; WM = working memory.

CHAPTER 4: DISCUSSION

This is the first experimental study to demonstrate a functional relationship between working memory and children's attentive behavior. All children's attentive behavior decreased as working memory demands increased, with the magnitude of these changes significantly greater for children with ADHD relative to typically developing children. Children with ADHD were significantly less attentive under even the lowest working memory set size conditions, and these rates were nearly identical to those observed in regular education classroom settings based on a recent meta-analytic review (i.e., 75% attentive; Kofler et al., 2008). In addition, robust correlations (Cohen, 1992) were found between children's attentive behavior during the working memory tasks and standardized teacher ratings[4] of their inattention at school (r = -.40 to -.46). Collectively, these findings suggest that the working memory demands manipulated experimentally in a controlled laboratory setting may be similar to those required in classroom settings.

Additional analyses were undertaken to address the central hypotheses of the study, viz., whether children's inattentive behavior is related to impaired central executive processes, results from overwhelming storage/rehearsal processes, or occurs due to impairments in both central executive and subsystem processes. Analyzing attentive behavior during conditions at or below each child's working memory capacity revealed that central executive processes accounted for large magnitude decreases in attentive behavior for children with ADHD, but diminutive decreases for typically developing children (i.e., 16% vs. 3%, respectively). This finding is consistent with previous investigations reporting larger magnitude central executive relative to

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[4] TRF ADHD Problems Inattention Subscale

phonological or visuospatial storage/rehearsal deficits in children with ADHD (Marzocchi et al., 2008; Martinussen et al., 2005; Rapport, Alderson et al., 2008; Willcutt et al., 2005), and extends previous findings by demonstrating that these deficits are functionally related to children's inattentiveness. The analyses also revealed that imposing task demands that exceed children's storage/rehearsal capacity was associated with similar magnitude decreases in attentive behavior for both groups (i.e., a decrease of approximately 9%). Children with ADHD, however, were overwhelmed under lower set size conditions relative to typically developing children. Specifically, the median working memory span for typically developing children was five stimuli for both the phonological and visuospatial tasks in contrast to four and fewer than three stimuli for children with ADHD, respectively. This finding is consistent with previous studies documenting moderately impaired storage/rehearsal capacities in children with ADHD, with larger magnitude visuospatial relative to phonological impairments (Martinussen et al., 2005; Willcutt et al., 2005).

Collectively, our results indicate that deficient central executive processes are associated with the largest magnitude decreases in attention for children with ADHD even at memory loads they are capable of handling. The most likely central executive candidate responsible for these deficits is the *internal focus of attention*. The other two central executive processes – divided attention, and the interplay between working memory and long-term memory – are less appealing candidates for several reasons. None of the tasks used in the study required divided attention, and demands on long-term memory were minimal due to the use of overlearned and readily activated stimuli such as single digit numbers, letters, and familiar shapes (circles). This inference is also supported by the finding that children with ADHD were not more inattentive than typically developing children after controlling for their working memory deficits, but continued to demonstrate impaired working memory deficits after accounting for their observed inattentive behavior.

The failure of previous research to consistently find impaired focused and selective attention processes in ADHD appears at odds with the current findings. These studies, however, have conventionally used experimental paradigms that require children to visually recognize and/or discriminate among previously learned stimuli while ignoring visual or auditory distracters (i.e., *external* focus of visual attention). The *internal* focus of attention, in contrast, is distinct but analogous to the *external* focus of visual attention, and is used to access and update individual stimuli currently active in the storage/rehearsal subsystems (Cowan, 2005; Garavan, 1998; Oberauer, 2003). The distinction between the internal and external foci of attention is supported by recent evidence that performance on traditional visual attention tasks such as the *n*-back and continuous performance task (CPT) is unrelated to performance on working memory span tasks (Kane, Conway, Miura, & Colflesh, 2007). Moreover, experimenter-paced tasks that require internal working memory processing and rehearsal appear to best distinguish children with ADHD from typically developing children relative to tasks in which response stimuli are present during the test phase (Rapport, Chung, Shore, Denney, & Isaacs, 2000). Additional studies are needed to address empirically whether particular central executive processes are distinctly deficient in children with ADHD relative to typically developing children, and whether these deficits render them more susceptible to internal interference effects (Oberauer, 2003; Kane, Bleckley, Conway, & Engle, 2001).

Prevailing hypotheses suggest that inattentive behavior is a ubiquitous feature of ADHD, but that its frequency is impacted by task and situational demands (cf. Kofler et al., 2008). The current results are consistent with this oft-replicated finding, and extend previous findings by generating testable hypotheses regarding specific mechanisms responsible for differences in attentive behavior across tasks and settings. Specifically, the current finding – that children with ADHD are not less attentive than typically developing children after accounting for their working memory deficits – may help explain anecdotal parent and teacher reports that children with ADHD remain engaged in particular tasks and activities with no apparent deficits in attention (e.g., watching TV, playing video games), yet experience significant difficulty maintaining attention during most in-seat academic/learning activities (e.g., homework, classroom academic assignments).

The current results may also help explain why behavioral interventions targeting inattentive behavior are effective, but fail to generalize to other situations and/or over time for children with ADHD (Jensen et al., 2007; Molina et al., 2009), and often fail to result in improved academic functioning (Rapport et al., 2000). Effective behavioral programs externalize several central executive and storage/rehearsal functions by providing frequent verbal and visual reminders of task instructions and specific behavioral expectations. In doing so, auditory feedback (e.g., verbal redirection) gains automatic access to the phonological storage/rehearsal subsystem (Baddeley, 2007) and may help replenish children's working memory with relevant information after it has faded, providing them an opportunity to successfully resume a required task (i.e., become attentive). As a result, curricula systems and interventions designed specifically to reduce central executive and storage/rehearsal demands in the classroom and at home may hold considerable promise for improving attentive behavior in children with ADHD. These techniques involve restructuring complex tasks to simplify mental processing, such as encouraging the use of memory aids, providing written instructions, simplifying multi-step directions, and using poster checklists (cf. Gathercole & Alloway, 2008). Targeting core deficits of ADHD such as working memory – as opposed to secondary behavioral symptoms such as inattention and hyperactivity – may prove more efficient and beneficial relative to traditional behavioral treatments. These strategies, however, are also unlikely to generalize across settings or over time.

Efforts to develop interventions that promote the early development of working memory abilities, and particularly central executive processes, appear warranted based on accumulating evidence and the current finding that children with ADHD become significantly more inattentive than their peers even under conditions that do not overwhelm their storage/rehearsal capacities. To date, however, there is scant empirical support to indicate that direct training of working memory in children is beneficial (for an exception, cf. Klingberg et al., 2005). The current findings, however, indicate that early attempts to train working memory in children with ADHD may have focused on the wrong elements of working memory – viz., training primarily storage/rehearsal capacity rather than the central executive processes functionally related to both inattentive and hyperactive behavior (Rapport et al., 2009). Finally, prevention rather than intervention approaches may provide maximum benefit if young children at risk for working memory deficits are targeted prior to critical periods in cognitive development, consistent with evidence that all working memory components are in place by age four (Alloway et al., 2006), and are highly predictive of working memory abilities and academic outcomes throughout childhood and adolescence (Gathercole, Pickering, Knight, & Stegmann, 2004; Gathercole & Alloway, 2008).

The unique contribution of the current study was the objective measurement of attentive behavior during concurrent manipulation of phonological, visuospatial, and central executive working memory demands while controlling for age, SES, and IQ-WM covariation. Several caveats require consideration when interpreting the present findings despite these and other methodological refinements (e.g., pre/post attentive behavior measurement). Independent experimental replication with larger samples that include females, older children, and other ADHD subtypes are always needed to assess the generalizability of highly controlled laboratory experiments with stringent inclusion criteria. Our sample size was sufficient, however, based on the a priori power analysis, and the degree of ODD comorbidity in the current study may be viewed as typical based on recent epidemiological findings (i.e., 59%; Wilens et al., 2002). In addition, ecological validity concerns were addressed partially by the robust correlations between the objective observations of children's attentive behavior used in the current study and teacher ratings of inattention at school. Finally, the large magnitude between-group differences in attentive behavior during our working memory tasks may be related to our stringent inclusion criteria, and attenuated to the extent that children exhibit fewer or less disabling ADHD symptoms. This hypothesis is consistent with accumulating evidence that ADHD behavioral symptoms represent continuous rather than categorical dimensions (Levy, Hay, McStephen, Wood, & Waldman, 1997), and the strong genetic contribution associated with attentive behavior (Gjone, Stevenson, & Sundet, 1996).

Current and past findings collectively indicate that hyperactive and inattentive behaviors in children with ADHD are functionally related to central executive impairments (Rapport et al., 2009), and that attention is impaired to a similar extent in children with ADHD and typically developing children when their storage/rehearsal subsystems are overwhelmed. These findings collectively provide strong support for empirical models that describe working memory deficits as core features of ADHD (Barkley, 1997; Rapport et al., 2001), and reveal that working memory deficits appear to account for two of the primary behavioral symptoms (i.e., inattention and hyperactivity) driving clinical referrals for ADHD (Pelham et al., 2005). Broader neurocognitive models of executive functions that include working memory, however, have lost favor in recent years secondary to the failure of neurocognitive test batteries to consistently implicate specific executive functioning deficits across studies (Nigg, Willcutt, Doyle, & Sonuga-Barke, 2005; Willcutt et al., 2005). These inconsistent findings, however, may be due to inadequate structural validity of commonly used test batteries for measuring specific deficits or traits (Clark & Watson, 1995). For example, the working memory subtests on the WISC-IV and common neuropsychological batteries contain measures of the phonological but not visuospatial system, and rely heavily on measures of storage/rehearsal (i.e., digits forward and backward) rather than central executive processing abilities (Engle et al., 1999; Swanson & Kim, 2007). Consequently, these measures tend to assess the least impaired components of working memory in children with ADHD (Martinussen et al., 2005). Future studies investigating executive functions in general, and working memory impairments in particular, will need to address these issues when developing structurally valid paradigms to further isolate the specific central executive impairments responsible for the behavioral symptoms of ADHD, in anticipation of developing targeted early intervention and prevention programs.

APPENDIX: IRB HUMAN SUBJECTS APPROVAL

University of Central Florida Institutional Review Board
Office of Research & Commercialization
12201 Research Parkway, Suite 501
Orlando, Florida 32826-3246
Telephone: 407-823-2901, 407-882-2012 or 407-882-2276
www.research.ucf.edu/compliance/irb.html

EXPEDITED CONTINUING REVIEW APPROVAL NOTICE

From : **UCF Institutional Review Board**
FWA00000351, Exp. 5/07/10, IRB00001138

To : **Mark Rapport and Valerie Sims**

Date : **March 13, 2008**

IRB Number: **SBE-07-04348**

Study Title: **Attention Deficit/Hyperactivity Disorder (ADHD): The Role of Working Memory as a Core Deficit**

Dear Researcher,

This letter serves to notify you that the continuing review application for the above study was reviewed and approved by the IRB Vice-chair on **3/12/2008** through the expedited review process according to 45 CFR 46 (and/or 21 CFR 50/56 if FDA-regulated).

Continuation of this study has been approved for a one-year period. The expiration date is 3/11/2009. This study was determined to be no more than minimal risk and the categories for which this study qualified for expedited review are:

6. Collection of data from voice, video, digital, or image recordings made for research purposes.

7. Research on individual or group characteristics or behavior (including, but not limited to, research on perception, cognition, motivation, identity, language, communication, cultural beliefs or practices, and social behavior) or research employing survey, interview, oral history, focus group, program evaluation, human factors evaluation, or quality assurance methodologies.

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. Subjects or their representatives must receive a copy of the consent form(s).

All data must be retained in a locked file cabinet for a minimum of three years (six if HIPAA applies) past the completion of this research. Any links to the identification of participants should be maintained on a password-protected computer if electronic information is used. Additional requirements may be imposed by your funding agency, your department, or other entities. Access to data is limited to authorized individuals listed as key study personnel.

To continue this research beyond the expiration date, a Continuing Review Form must be submitted 2 – 4 weeks prior to the expiration date. Use the Unanticipated Problem Report Form or the Serious Adverse Event Form (within 5 working days of event or knowledge of event) to report problems or events to the IRB. Do not make changes to the study (i.e., protocol methodology, consent form, personnel, site, etc.) before obtaining IRB approval. Changes can be submitted for IRB review using the Addendum/Modification Request Form. An Addendum/Modification Request 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 .

On behalf of Tracy Dietz, Ph.D., UCF IRB Chair, this letter is signed by:

Signature applied by Joanne Muratori on 03/13/2008 08:59:06 AM EST

Joanne Muratori

IRB Coordinator

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