

ADHD and Working Memory: The Impact of Central Executive Deficits and Exceeding Storage/Rehearsal Capacity on Observed Inattentive Behavior

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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 deficits and inattentive behavior. The current study investigated whether inattentive behavior in children with ADHD is functionally related to the 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 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) exceeding 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.

Keywords ADHD · Working memory · Attention · Central executive

Introduction

Recent meta-analytic (Martinussen et al. 2005; Willcutt et al. 2005) and experimental (Brocki et al. 2008; Rapport et al. 2008a) 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. Extensive neuropsychological, neuroanatomical, neuroimaging, and factor analytic investigations support the distinct functioning of the two subsystems, their storage and rehearsal components, and the domain-general central executive (Baddeley 2007).

The question of whether deficiencies in specific underlying mechanisms or processes are unique to a particular disorder such as ADHD is central to child psychopathology theory development. Recent studies have begun to address this question with respect to the functional working memory model of ADHD (Rapport et al. 2001, 2008b).

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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; Martinussen et al. 2005; Rapport et al. 2008a). The central executive component of working memory is also functionally related 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 et al. 2005). Significant correlations between laboratory measures of working memory and teacher ratings of classroom inattention are usually (Lee et al. 2004; Thorell 2007) but not always reported (Rucklidge and Tannock 2002), and range from -0.20 to -0.46 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 min 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.

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 or “zone out” (p. 71) as the quantity of information to be processed exceeds their working memory capacities (Gathercole and Alloway 2008). Kane et al. (2007a) 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 phonological and visuospatial storage/rehearsal components of Baddeley's (2007) working memory model are thus particularly appealing candidates to explain the inattentive behavior typically observed in children with ADHD during academic and other activities that may exceed the limited capacity of either storage/rehearsal component. No study to date, however, has objectively measured attentive behavior while concurrently manipulating demands on the phonological and

visuospatial storage/rehearsal systems to determine whether increasing demands on these components is functionally related to decreased attentive behavior in children.

The domain-general central executive component of Baddeley's (2007) working memory model is another promising candidate to explain the inattentive behavior observed in children with ADHD, given its pivotal role in controlling and focusing attention (Baddeley 2007), large magnitude impairment in ADHD (Rapport et al. 2008a), and functional relationship with hyperactive behavior (Rapport et al. 2009). The collective results of 25 years of research investigating potential cognitive processes associated with central executive functioning, however, have failed to reliably demonstrate ADHD-related impairments in focused (van der Meere and Sergeant 1988) and selective attention (Huang-Pollock et al. 2005; Lajoie et al. 2005; Sergeant and Scholten 1983). Moreover, empirical studies have demonstrated a normal (van der Meere and Sergeant 1987) or unimpaired (van Mourik et al. 2007) response to distractions, and intact visual orienting processes in children with ADHD (Huang-Pollock and Nigg 2003). Studies of divided attention are equivocal, with some studies reporting superior (Koschack et al. 2003), similar (Lajoie et al. 2005; van der Meere and Sergeant 1987), or impaired (Tucha et al. 2006) divided attention abilities in children with ADHD relative to typically developing children.

The current study uses three distinct tasks to test specific hypotheses concerning the potential relationship between working memory components and inattentive behavior in children: (a) pre- and post-test control conditions that place no demands on the central executive and subsystem storage/rehearsal processes, and provide an experimental means by which to examine the effects of systematically imposing demands on working memory component processes; (b) a phonological working memory task administered at four distinct set sizes (i.e., increasing the number of stimuli to be mentally manipulated and recalled); and (c) a visuospatial working memory task administered at four distinct set sizes. According to Baddeley (2007), central executive demands increase from control to working memory conditions, and remain stable across increasing set size (i.e., central executive processing demands are equivalent across working memory set size conditions). Conversely, demands on storage/rehearsal processes increase from control to working memory conditions, and increase incrementally under heavier set size conditions. These tenets of Baddeley's (2007) model are tested specifically in the Tier II analyses, and support the following predictions: If ADHD-related inattentive behavior is related primarily to modality-specific (phonological, visuospatial) storage/rehearsal deficiencies, systematically increasing set size should correspond with incremental *decreases* in attentive behavior. In addition,

significant differences should be apparent between conditions that do and do not exceed the child's working memory span. Conversely, if inattentive behavior in ADHD is related primarily to central executive dysfunction, observed rates of attentive behavior should decrease significantly from control to working memory conditions, and remain stable across increasing phonological and visuospatial set size conditions due to the unchanging processing requirements. Finally, children's inattentive behavior may be related to both impaired central executive and storage/rehearsal processes. In this case, attentive behavior is expected to decrease initially relative to control conditions due to impaired central executive functioning needed to process stored stimuli (Oberauer 2003), continue to decrease as a function of increasing storage demands (larger stimulus set sizes), and become particularly evident as storage demands exceed storage/rehearsal capacity.

Method

Participants

The sample was comprised of 29 boys aged 8 to 12 years ($M=9.73$, $SD=1.36$), recruited by or referred to a Children's Learning Clinic (CLC) through community resources (e.g., pediatricians, community mental health clinics, school system personnel, 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 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 0.93 to 1.00, test-retest reliability of 0.63 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'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 *SDs* above the mean on the Attention-Deficit/Hyperactivity Problems DSM-Oriented scale of the Child Behavior Checklist (CBCL; Achenbach and Rescorla 2001), or exceeding the criterion score for the parent version of the ADHD-Combined subtype subscale of the Child Symptom Inventory (CSI; Gadow et al. 2004); and (3) teacher ratings of at least 2 *SDs* above the mean on the Attention-Deficit/Hyperactivity Problems DSM-Oriented scale of the Teacher Report Form (TRF; Achenbach and 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 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 et al. 2008b). All children in the ADHD group met criteria for ADHD-Combined Type, and six were comorbid for Oppositional Defiant Disorder (ODD). None of the children were comorbid for additional DSM-IV childhood disorders.

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 within 1.5 *SDs* of the mean on all CBCL 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. Eight children were excluded because they met DSM-IV criteria for childhood disorders other than ADHD. 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.

Table 1 Sample and Demographic Variables

Variable	ADHD		Typically developing		
	\bar{X}	<i>SD</i>	\bar{X}	<i>SD</i>	<i>F</i>
Age	9.22	1.06	10.29	1.46	5.12*
FSIQ ^a	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***

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

^a Significant between-group differences in FSIQ were eliminated when residual FSIQ unrelated to working memory was computed. Residual FSIQ values are not shown because they are not directly interpretable relative to their original metric

* $p \leq 0.05$, *** $p \leq 0.001$

Measures

Visual attention to task A ceiling-mounted digital video camera was used to record children's attentive behavior while they completed each of the tasks described below. For each child, two observers used *The Observer 5.0* (Noldus Information Technology 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 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). Research assistants were trained extensively and required to obtain a minimum percent agreement of 0.80 compared to a gold standard practice tape as a prerequisite to coding participants. Interrater reliability was tested for all observation days. Overall percent agreement across all tapes was 0.94, with a kappa of 0.88.

Phonological (PH) working memory task The phonological working memory task is similar to the Letter-Number Sequencing subtest on the WISC-IV, 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. 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. The columns were offset from a standard 3×3 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 serial position of the red dot last. The last response was followed by an intertrial interval of 1,000 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 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 behavior (e.g., fatigue effects). The program was also selected to provide an experimental means by which to make comparisons between tasks that require (eight working memory conditions) and do not require (pre-post control conditions) central executive processing (Baddeley 2007). 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 $p > 0.25$).

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 calculated based on the ten primary subtests, but was not analyzed as a covariate for conceptual reasons—it would result in removing substantial variance associated with working memory from working memory due to their shared variance (Rapport et al. 2009). A residual FSIQ score was derived to correct for this problem. Briefly, the derived central executive, phonological storage/rehearsal, and visuospatial storage/rehearsal composite performance variables described below were covaried out of FSIQ ($R^2 = 0.33$, $p = 0.02$) to estimate IQ that is unrelated to working memory.

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. 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 h 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. Details concerning the administration of practice blocks for the visuospatial and phonological paradigms are described in

Rapport et al. (2008a). The eight working memory set size conditions each contained 24 unique trials of the same stimulus set size, and were counterbalanced across the four testing sessions to control for order effects and proactive interference across set size conditions (Conway et al. 2005). The control conditions always occurred as the first and last tasks each day.

Dependent variables Attentive behavior (percent oriented) refers to the percentage of time during each of the task conditions (C1, VS and PH set sizes 3, 4, 5, and 6, and C2) that children were visually attending to the task. Performance data was calculated according to recommendations by Conway et al. (2005). Stimuli incorrect per trial for each set size reflected the average number of *stimuli* that children did not reorder and recall in the correct phonological or visuospatial serial location¹, and was used for latent variable analyses to statistically isolate working memory performance attributable to central executive and subsystem storage/rehearsal functioning. Percentage of trials correct reflected the number of *trials* at each set size for which each child correctly responded to all stimuli, and was used to determine each child's working memory span.

Results

Data Screening

Power Analysis GPower software version 3.0.5 (Faul et al. 2007) was used to determine needed sample size using an effect size (ES) estimate of 1.40 based on a recent meta-analytic review of observed classroom inattention (Kofler et al. 2008); power was set to .80 as recommended by Cohen (1992). For an ES of 1.40, $\alpha = 0.05$, power ($1 - \beta$) = 0.80, two groups, and six 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_0 . Twenty-nine children participated in the current study.

Preliminary Analyses

Each of the task conditions (C1, PH set sizes 3–6, VS set sizes 3–6, C2) were screened for univariate and multivariate outliers and tested against $p < 0.001$. A value equal to one

¹ For example, if the correct response was “2 4 5 6 H”, and a child responded “2 3 4 **6 H**”, then the child correctly identified 3 stimuli (correct responses in bold), and incorrectly identified 2 stimuli.

smaller than the next most extreme score was substituted for one subject's post baseline and one subject's visuospatial set size 6 score.

Sample ethnicity was mixed with 18 Caucasian (62%), seven Hispanic (24%), two African American (7%), and two 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). Observed inattentive behavior across the eight working memory set size conditions was correlated significantly with teacher ratings of inattention at school (TRF ADHD Problems Inattention Subscale: $r=-0.40$ to -0.46 , all $p<0.05$). Children with ADHD and TD children differed on age ($p=0.03$), and SES ($p=0.04$). 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, or III, analyses (all $p\geq.11$). Initial group differences in FSIQ (Table 1) were no longer apparent after residualizing for working memory ($p=0.92$; see *Measured Intelligence*). We therefore report simple model results with no covariates.

Tier I: Set Sizes

The first set of analyses examined the effects of increasing phonological and visuospatial set size on children's attentive behavior (see Tables 2 and 3). Using Wilks' criterion, a significant one-way MANOVA on all ten task conditions (C1, set sizes 3–6 for both modalities, C2) by group (ADHD, TD) confirmed the overall relationship between attentive behavior and WM, Wilks' $\lambda=0.27$, $F(10,18)=4.98$, $p=0.002$. 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 (Fig. 1).

Phonological ANOVA The Mixed-model ANOVA was significant for group, set size, and the group by set size interaction (all $p<0.0005$) 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 $p\leq 0.009$). The pattern of attentive behavior as storage/rehearsal 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 $p\leq 0.02$). No significant differences were observed between set sizes 3 and 4 ($p=0.93$), or set sizes 5 and 6 ($p=0.75$; ADHD: $C1=C2>3=4>5=6$). In contrast, the

Table 2 Phonological Set Size Analyses

	Phonological set size ^a						Group composite \bar{X} (SE)	F	Set size contrasts
	C1 \bar{X} (SD)	3 \bar{X} (SD)	4 \bar{X} (SD)	5 \bar{X} (SD)	6 \bar{X} (SD)	C2 \bar{X} (SD)			
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 ^b	1.39	1.27	2.01	1.52	0.25 ^b			

A ADHD, C control condition, TD typically developing children

^a Phonological group \times set size interaction, $F(5,125)=8.14$, $p=0.001$, ** $p\leq 0.01$, *** $p\leq 0.001$

^b 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 ^a						Group composite \bar{X} (SE)	F	Set size contrasts
	C1 \bar{X} (SD)	3 \bar{X} (SD)	4 \bar{X} (SD)	5 \bar{X} (SD)	6 \bar{X} (SD)	C2 \bar{X} (SD)			
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 ^b	1.13	1.68	1.91	1.09	0.25 ^b			

A ADHD, C control condition, TD typically developing children

^a Visuospatial group × set size interaction, $F(5,135)=8.11, p \leq 0.001, **p \leq 0.01, ***p \leq 0.001$

^b 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

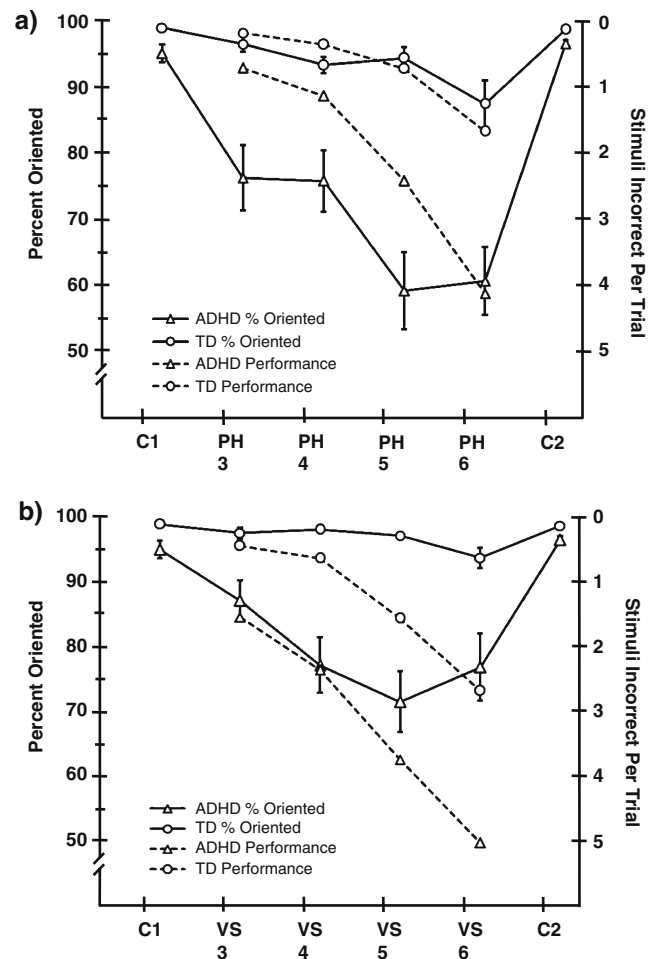


Fig. 1 Attentive behavior during control and **a** phonological and **b** visuospatial working memory tasks. *Solid lines* represent attentive behavior (*left ordinate*); *dashed lines* represent stimuli incorrect per trial (*right ordinate*). *Error bars* reflect *standard error*. *ADHD* attention-deficit/hyperactivity disorder; *TD* typically developing

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 $p \leq 0.05$; TD: C1=C2>3=4=5>6). No differences were observed between the pre and post control conditions for either group (both $p \geq 0.18$).

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 Fig. 1a.

Visuospatial ANOVA The Mixed-model ANOVA was significant for group, set size, and the group by set size interaction (all $p < 0.0005$) 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 $p \leq 0.009$). The pattern of attentive behavior as storage/rehearsal demands increased, however, was appreciably different between groups. Children with ADHD were significantly more attentive ($p \leq 0.04$; all other $p \geq .14$) during both control conditions relative to higher set size conditions (ADHD: $C1=C2>3>4=5=6$). TD children were similarly attentive across most conditions (all $p \geq 0.06$) before decreasing significantly at the highest set sizes ($p \leq 0.03$; 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 Fig. 1b.

Tier II: Components of Working Memory

A three-step process was used to estimate the relative contribution of central executive and storage/rehearsal processes to children's attentive behavior. Baddeley's (2007) assertion that central executive demands remain constant despite increasing set size was examined initially. Children's individual working memory spans were determined subsequently and used to categorize attentive behavior into three conditions, with changes across conditions attributable to specific working memory components and tested with a Mixed-model ANOVA.

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. Engle et al. 1999). Shared variance between phonological and visuospatial stimuli incorrect per trial at each set size reflects domain-general central executive functioning, whereas unique variance reflects phonological and visuospatial storage/rehearsal functioning, respectively (Swanson and 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 ($r=0.76$ to 0.90 , all $p < 0.0005$). Phonological and visuospatial storage/rehearsal variables, in contrast, were correlated for adjacent set size conditions (e.g., set size 3

with 4, 4 with 5, and 5 with 6; $r=0.41$ to 0.71 ; all $p < 0.002$), but not significantly correlated for set size conditions differing by two or more stimuli (all $p > 0.10$). 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 (Fig. 2). The findings also substantiate the use of the procedure described below.

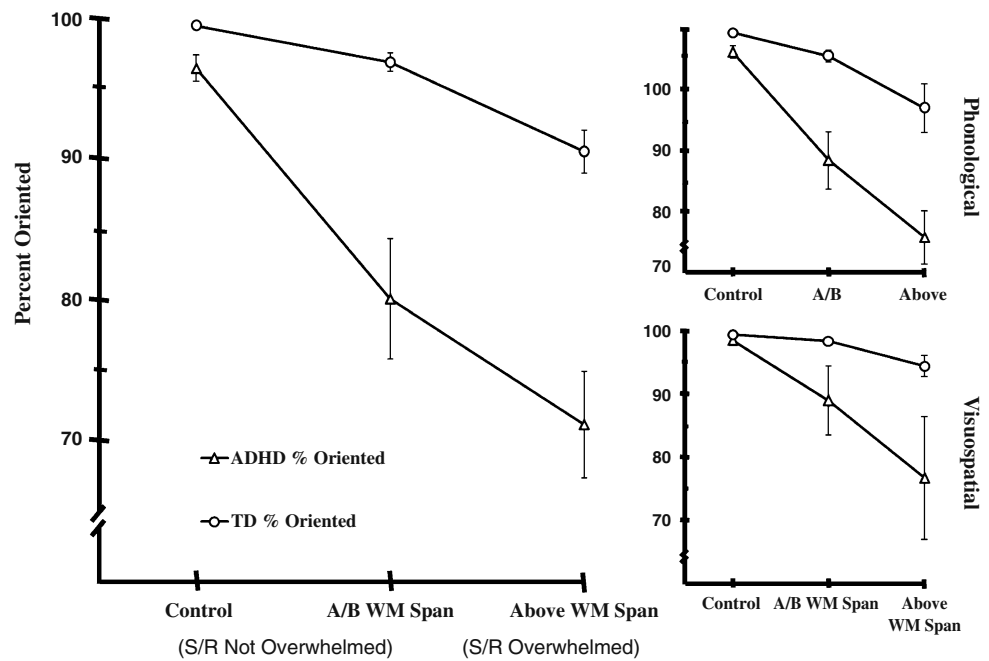
Performance scores (% of trials correct) were examined to determine each child's working memory span, defined as the maximum set size at which a child successfully recalls all stimuli in the correct serial order on at least 50% of trials (Conway et al. 2005). Attentive behavior rates for each child were 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. Based on Baddeley's (2007) model and the preceding analyses, changes in attentive behavior between control and conditions at/below working memory span are attributable to central executive demands, and changes in attentive behavior from conditions at/below to exceeding working memory span are attributable to exceeding children's storage/rehearsal capacities (Fig. 2). 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 $n=12$) to maximize power.

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 (Fig. 2). The Mixed-model ANOVA was significant for group, $F(1,24)=22.66$, $p < 0.0005$, working memory span, $F(2,48)=28.59$, $p < 0.0005$, and the group by span interaction, $F(2,48)=7.51$, $p=0.001$. 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 $p \leq 0.04$). 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, 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 III: 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

Fig. 2 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; *CE* central executive; *S/R* storage/rehearsal; *TD* typically developing; *WM* working memory



behavior across all conditions represent ubiquitous inattentive behavior in children with ADHD or the influence of working memory demands (Rapport et al. 2008b). Residual attentive behavior scores for all eight working memory conditions were computed by regressing working memory performance (stimuli incorrect per trial) onto attentive behavior rates at each phonological (R^2 range: 0.28 to 0.47) and visuospatial (R^2 range: 0.19 to 0.43) 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 $p \geq 0.09$), condition (both $p = 1.0$), and the group by condition interaction (both $p \geq 0.28$), 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 $p \leq 0.004$), and the phonological ($p = 0.03$) but not visuospatial ($p = 0.06$) group by set size interaction. 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.

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.

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 when they were required to process a greater number of phonological and visuospatial stimuli, and the magnitude of these changes was 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 were found between children’s attentive behavior during the working memory tasks and standardized teacher ratings of their inattention at school ($r = -0.40$ to -0.46). Collectively, these findings suggest that the working memory demands manipulated experimentally in a con-

trolled 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 exceeding 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 phonological or visuospatial storage/rehearsal deficits in children with ADHD (Martinussen et al. 2005; Rapport et al. 2008a; 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%), although this decrease occurred under lower set size conditions for children with ADHD. 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 set sizes they are capable of handling. The most likely central executive candidate responsible for these deficits is the focus of attention component. 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. Divided attention processes were not required because only one task was administered at any given time (Baddeley 2007), 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 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). Successful performance on these recognition paradigms does not require a specific selection mechanism *within* working memory because the information is displayed visually during the response phase of the task (Cabeza et al. 1997; Kahana et al. 2005; MacLeod and 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 cognitively without the benefit of external visual cues, while minimizing potential internal and external effects that may interfere with this process (Garavan 1998; Oberauer 2003). The internal focus of attention is thus analogous to but distinct from the *external* focus of visual attention. 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 et al. 2007b). 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 et al. 2000). Additional studies are needed to address empirically whether distinct central executive processes, such as the internal focus of attention, are 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 et al. 2001).

Prevailing hypotheses suggest that inattentive behavior is a central feature of ADHD, and 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 and processes 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).

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 exceed their storage/rehearsal capacities. To date, however, there is scant empirical support to indicate that direct training of working memory in children is beneficial. 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 processing deficits functionally related to both inattentive and hyperactive behavior (Rappport 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 et al. 2004; Gathercole and 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 symp-

toms represent continuous rather than categorical dimensions (Levy et al. 1997).

Current and past findings collectively indicate that inattentive and hyperactive behaviors in children with ADHD are functionally related to central executive impairments (Rappport et al. 2009), and that attention is impaired to a similar extent in children with ADHD and typically developing children when task demands exceed their storage/rehearsal capacities. These findings collectively provide strong support for empirical models that describe working memory deficits as core features of ADHD (Barkley 1997; Rappport 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 et al. 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. 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 and 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.

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