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Competing Core Processes in Attention-Deficit/Hyperactivity Disorder (ADHD): Do Working Memory Deficiencies Underlie Behavioral Inhibition Deficits?

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Abstract The current study examined competing predictions of the working memory and behavioral inhibition models of ADHD. Behavioral inhibition was measured using a conventional stop-signal task, and central executive, phonological, and visuospatial working memory components (Baddeley 2007) were assessed in 14 children with ADHD and 13 typically developing (TD) children. Bootstrapped mediation analyses revealed that the visuospatial working memory system and central executive both mediated the relationship between group membership (ADHD, TD) and stop-signal task performance. Conversely, stop-signal task performance mediated the relationship between group membership and central executive processes, but was unable to account for the phonological and visuospatial storage/rehearsal deficits consistently found in children with ADHD. Comparison of effect size estimates for both models suggested that working memory deficits may underlie impaired stop-signal task performance in children with ADHD. The current findings therefore challenge existing models of ADHD that describe behavioral inhibition as a core deficit of the disorder.

Keywords Attention-deficit/hyperactivity disorder · ADHD · Behavioral inhibition · Stop-signal task · Working memory

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Executive functions play a central role in current (Barkley 2006; Rapport et al. 2008a; Sonuga-Barke 2002) models of ADHD, and generally refer to control processes involving prefrontal/frontal cortical areas that allow for the execution, regulation, planning, and inhibition of behavior. Deficits of both behavioral inhibition and working memory—two executive functions that have garnered particular attention in extant models of the disorder—have been included in prominent theories of ADHD, but vary with regard to their central role as a core deficit of the disorder. The functional working memory model of ADHD proposes that working memory deficits are a central core component (Rapport et al. 2001, 2008b) or candidate endophenotype of the disorder (Castellanos and Tannock 2002), whereas other models suggest that working memory deficits are secondary to underlying deficits in behavioral inhibition (Barkley 1997; Sonuga-Barke 2002).

Behavioral inhibition models of ADHD argue that inhibitory processes are unable to effectively prevent extraneous information from entering the working memory system, resulting in an inability to maintain task goals without interference (Brocki et al. 2008). Behavioral inhibition is hypothesized as a cognitive process that sub-serves behavioral regulation and executive function (Barkley 2006), and underlies the ability to withhold or stop an on-going response (Schachar et al. 2000). According to Logan et al.'s (1984) behavioral inhibition model, response inhibition depends on whether a stop-process can overtake a go-process when the go- and stop-processes are activated in close temporal sequence (i.e., go-signal activation followed by stop-signal activation). A slow reaction time to a stop-stimulus decreases the probability that the stop-process will overtake the go-process. The stop-signal task is considered the premier measure used in clinic- and laboratory-based research to investigate behavioral inhibition in children with ADHD due to its ability to capture theoretically important cognitive processes by means of the stop-signal reaction time (SSRT) and/or stop-signal delay (SSD) metrics (Alderson et al. 2007).

The term *working memory* refers to a limited capacity system for the temporary storage and manipulation of information required to guide behavior. The working memory system is comprised of a central executive and two subsidiary components—the phonological and visuospatial storage/rehearsal subsystems (Baddeley 2007). The central executive (CE) 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 (PH) subsystem is responsible for the temporary storage and rehearsal of verbal material, whereas the visuospatial (VS) subsystem provides this function for non-verbal visual and spatial information. Alternative views within the field of neuropsychology suggest that working memory reflects a more general ability to maintain task goals and inhibit distracting, non-relevant information (Engle et al. 1999), and traditionally employ span tasks that place simultaneous demands on the CE and subcomponent processes (Engle et al. 1999; Swanson and Kim 2007). Extensive neuropsychological (Baddeley 2007), neuroanatomical (Smith et al. 1996), neuroimaging (Fassbender and Schweitzer 2006), and factor analytic (Alloway et al. 2006) investigations, however, support the distinct functioning of the two subsystems and their buffer-rehearsal components.

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 system, followed by visuospatial storage/rehearsal and then phonological storage/rehearsal subsystems (i.e., deficits in CE>VS>PH; Marzocchi et al. 2008; Rapport et al. 2008a; Martinussen et al. 2005; Willcutt et al. 2005). ADHD-related deficits in the central executive component of working memory are also functionally related to inattentive (Kofler et al. 2009) and hyperactive behavior (Rapport et al. 2009)—two of the three primary symptom clusters driving clinical referrals for ADHD (Pelham et al. 2005). The functional working memory model of ADHD, in contrast to behavioral inhibition models, holds that behavioral disinhibition is more parsimoniously viewed as a product of working memory processes rather than a cause thereof (Rapport et al. 2008b). This assertion is based on the observation that inhibition is a reaction to external stimuli that must first gain access to and be evaluated within working memory.

Extant studies utilizing varying iterations of a go/no-go task have reported significant correlations between behavioral inhibition and working memory in preschool (Sonuga-Barke et al. 2002) and school-aged (Brocki et al. 2008) children with ADHD. Only two studies, however, have examined the relationship between working memory and performance on the conventional stop-signal task[1]. Clark et al. (2007) reported a significant correlation between inhibition (stop-signal reaction time) and spatial working memory errors in adults with ADHD, and concluded that inhibition and working memory may originate from a common underlying deficit. A second study reported a significant correlation between phonological working memory (a counting task and a digit span backwards task) and performance on the stop-signal task among a collapsed group of children with ADHD and typically developing children (Mullane and Corkum 2007). The central findings of these studies imply significant shared variability between measures of behavioral inhibition and working memory; however, the directional relationship of behavioral inhibition and working memory could not be determined based on the correlational analyses employed.

The current study is the first to test opposing predictions stemming from the functional working memory (Rapport et al. 2001, 2008a) and behavioral inhibition (Barkley 1997; Sonuga-Barke 2002) models of ADHD by examining the directional relationship between constructs. Children with ADHD were predicted to have slower stop signal reaction times (SSRTs), similar stop signal delay times (SSDs), and poorer working memory performance relative to typically developing (TD) children based on previous meta-analytic reviews (Alderson et al. 2007; Martinussen et al. 2005). In addition, working memory in general, and central executive processes in particular, were predicted to mediate the relationship between group membership (ADHD, TD) and SSRT, but SSRT was not expected to significantly mediate the direct effect between group and working memory. This prediction was based on previous findings that suggest behavioral inhibition is downstream of working memory (Alderson et al. 2007, 2008). No predictions were offered concerning the mediation potential of working memory modalities (PH, VS) or storage/rehearsal components. The issue was examined, however, by statistically isolating the domain-general central executive and subsystem (PH, VS) processes, and subsequently testing each as potential mediators of behavioral inhibition. To our knowledge, this is the first study that examines the directional relationship between working memory components (storage/rehearsal, central executive) and stop-signal behavioral inhibition.

[1] Lee et al. (2004) tested the divergent predictions of the working memory (Rapport et al. 2008b) and inhibition (Barkley 2006) models of ADHD, and found that working memory mediated the relationship between cognitive disinhibition and teacher-reported attention problems. The distinction between cognitive and behavioral inhibition, however, is well documented and suggests that these findings may only generalize to a select component of the inhibition model (Nigg 2001).

Method

Participants

The sample was comprised of 27 boys aged 8 to 12 years (M=9.76, SD=1.40), recruited by or referred to the Children's Learning Clinic (CLC) through community resources (e.g., pediatricians, community mental health clinics, school system personnel, self-referral). Typically developing children (those without a suspected psychological disorder) were actively recruited through contact with neighborhood and community schools, family friends of referred children, and other community resources, and consisted primarily of self-referred families who were interested in learning more about their children's cognitive and academic strengths and weaknesses. Psychoeducational evaluations were 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; Kaufman et al. 1997). Additionally, all children's K-SADS interviews were supplemented with parent and teacher ratings scales, including the Child Behavior Checklist (CBCL; Achenbach and Rescorla 2001), Teacher Report Form (TRF; Achenbach and Rescorla 2001), and Child Symptom Inventory – Parent & Teacher (CSI; Gadow et al. 2004).

Fourteen 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 semi-structured interview with parent and child; (2) parent ratings of at least 2 *SD*s above the mean on the Attention Problems clinical syndrome scale of the CBCL, or exceeding the criterion score for the parent version of the ADHD-Combined subtype subscale of the CSI; and (3) teacher ratings of at least 2 *SD*s above the mean on the Attention Problems clinical syndrome scale of the TRF, or exceeding the criterion score for the teacher version of the ADHD-Combined subtype subscale of the CSI. Employing the either/or ratings scale criteria was adopted to improve diagnostic sensitivity and provide additional screening for the possible presence of comorbid clinical disorders in children. All children in the ADHD group met criteria for ADHD-Combined Type, and seven were comorbid for Oppositional Defiant Disorder (ODD).

Thirteen children met the following criteria and were included in the TD group: (1) no evidence of any clinical disorder based on parent and child K-SADS interview; (2) normal developmental history by maternal report; (3) ratings below 1.5 *SD*s on the clinical syndrome scales of the CBCL[2] and TRF; and (4) parent and teacher ratings within the non-clinical range on all CSI subscales.

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—seven of the children with ADHD had previously received trials of psychostimulant medication.

Measures

Behavioral Inhibition

Stop-signal Task The stop-signal task and administration instructions are identical to those described in Schachar et al. (2000). Go-stimuli are displayed for 1000 ms as uppercase letters X and O positioned in the center of a computer screen. Xs and Os appear with equal frequency throughout the experimental blocks. Each go-stimulus is preceded by a dot (i.e., fixation point) displayed in the center of the screen for 500 ms. The fixation point serves as an indicator that a go-stimulus is about to appear. A 1000 Hz auditory tone (i.e., stop-stimulus), delivered through sound-deadening headphones, is generated by the computer and presented randomly on 25% of the experimental trials. Stop-signal delays (SSD)—the latency between presentation of go- and stop-stimuli—are initially set at 250 ms, but dynamically adjusted ±50 ms contingent on a participant's performance on the previous trial. Successfully inhibited stop-trials are followed by a 50 ms increase in SSD, and unsuccessfully inhibited stop-trials are followed by a 50 ms decrease in SSD. The algorithm is designed to approximate successful inhibition on 50% of the stop-trials. A two-button response box is used wherein the left button is used to respond to the letter X, and the right button is used to respond to the letter O. All participants completed two practice blocks and eight consecutive experimental blocks of 32 trials (i.e., 24 go-trials, 8 stop-trials).

[2] One typically developing child had elevated parent ratings on three CBCL scales. K-SADS interview with parent and child revealed that these endorsements were highly specific to a recent parent-child interaction. CSI—Parent severity scores for this child were in the normal range.

SSRT and SSD were the primary measures of behavioral inhibition in the current study. Both metrics were examined due to disagreement in the literature regarding which variable best captures the behavioral inhibition construct. For example, recent meta-analytic (Alderson et al. 2007; Lijffijt et al. 2005) and experimental studies (Alderson et al. 2008) concluded that examination of between-group differences in mean SSD was the most direct measure of behavioral inhibition in stop-signal tasks that utilize dynamic stop-signal delays, given that SSDs change systematically according to inhibitory success or failure. Many studies, however, suggest that the derived SSRT[3] variable provides a more useful indicator of behavioral inhibition and do not investigate between-group differences in SSD (Huizenga et al. 2009; Marzocchi et al. 2008).

Working Memory

The number of stimuli correct per trial was used as the primary outcome measure for all visuospatial and phonological working memory tasks as recommended by Conway and colleagues (2005).

Visuospatial (VS) Working Memory Task Children were shown nine identical 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 stimulus 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.

Phonological (PH) Working Memory Task The PH working memory task is similar to the Letter-Number Sequencing subtest on the WISC-IV (Wechsler 2003), and assesses PH 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 number and letter (4 cm height) 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, independently recorded oral responses (interrater reliability=95.8% agreement).

VS Mediator Variables The number of stimuli correct per trial for each of the four stimulus set size blocks (3, 4, 5, 6) served as the primary dependent variable for assessing children's overall VS working memory performance (i.e., combined functioning of the central executive and VS storage/rehearsal). Composite VS scores were computed by averaging each child's score across set sizes to address questions concerning overall working memory differences among groups. Latent variable analyses were undertaken to determine the extent to which group differences in SSRT were mediated by 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; Swanson and Kim 2007). VS storage/rehearsal was estimated using the following procedures. PH composite scores were covaried from VS composite scores at each set size to remove common variance associated with the domain-general central executive (see Fig. 1). These four VS storage/rehearsal scores were then averaged to provide an overall estimate of the contribution of VS storage/rehearsal to performance on the VS task independent of shared central executive influences.

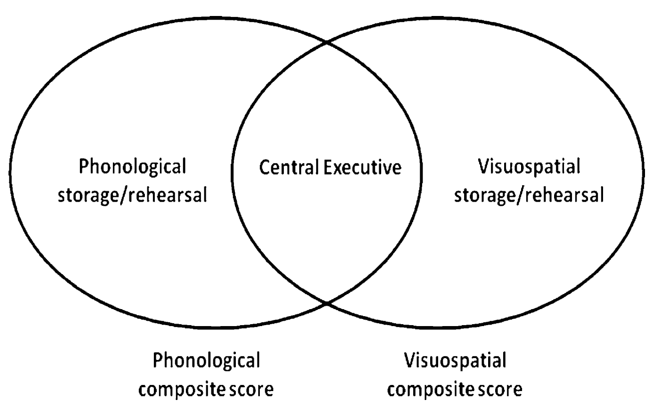

Fig. 1 Visual schematic of the component processes derived from the phonological (PH) and visuospatial (VS) tasks

[3] SSRT is unobservable and obtained by subtracting participants' mean SSD from MRT (SSRT=MRT-SSD).

PH Mediator Variables The number of stimuli correct per trial for each of the four stimulus set size blocks (3, 4, 5, 6) served as the primary dependent variable for assessing children's overall PH working memory performance (i.e., combined functioning of the central executive and PH storage/rehearsal). PH composite scores were computed by averaging each child's score across set sizes to address questions concerning overall working memory differences among groups. PH storage/rehearsal was estimated using the following procedures. VS composite scores were covaried from PH composite scores at each set size to remove common variance associated with the domain-general central executive. These four PH storage/rehearsal scores were then averaged to provide an overall estimate of the contribution of PH storage/rehearsal to performance on the PH task independent of shared central executive influences.

Central Executive Two unstandardized predicted scores were computed by regressing VS scores onto PH scores at each set size, and PH scores onto VS scores at each set size, then averaging these scores to provide an estimate of central executive functioning (i.e., shared variance between VS and PH scores).

Measured Intelligence All children were administered either the Wechsler Intelligence Scale for Children third or fourth edition (Wechsler 1991, 2003) to obtain an overall estimate of intellectual functioning. The changeover to the fourth edition was due to its release during data collection and to provide parents with the most up-to-date intellectual evaluation possible. Full Scale IQ (FSIQ) was not analyzed as a covariate because it shares significant variance with working memory and would result in removing substantial variance associated with working memory from working memory (Ackerman et al. 2005). Instead, a residual FSIQ score was derived using a latent variable approach (Rapport et al. 2009). Briefly, the derived central executive, phonological storage/rehearsal, and visuospatial storage/rehearsal performance variables described below were covaried out of FSIQ. Residual FSIQ scores represent IQ that is unrelated to estimated working memory 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. The phonological, visuospatial and stop-signal 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 the four phonological and four visuospatial conditions (i.e., PH and VS set sizes 3, 4, 5, and 6) across the four testing sessions, and the stop-signal task on one of the four testing days. 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 et al. (2008a). The eight working memory conditions and stop-signal task were counterbalanced to control for order effects. Children were seated approximately 0.66 m from the computer monitor for all tasks.

Mediation Analyses All mediation analyses were completed utilizing a bootstrapping procedure (Shrout and Bolger 2002). The bootstrap procedure is the recommended and preferred method for determining the statistical significance of a potential mediating variable (i.e., the indirect effect) for investigations with samples as small as 20 participants (Efron and Tibshirani 1993; Preacher and Hayes 2004). Significance of the indirect effect is determined by examining the 95% confidence interval (CI) of the sampling distribution of the mean. Confidence intervals that do not include zero are considered statistically significant at the 0.05 level. Following the recommendations of Shrout and Bolger (2002), 1000 samples were derived from the original sample (n=27) by a process of re-sampling with replacement. All variables were standardized prior to entry into mediation analyses, which allows the standardized β weights for each model to be interpreted as Cohen's d effect sizes when predicting from a dichotomous variable.

Inter-correlations between overall VS and PH working memory scores, VS and PH storage/rehearsal, the central executive, and behavioral inhibition (SSRT and SSD) were computed in Tier I of the analyses to determine whether mediation analyses were justified. The second and third data analytic tiers examine the extent to which working memory and behavioral inhibition serve as statistically significant mediators of one another.

Results

Outliers

Each of the independent and dependent variables were screened for univariate outliers, defined as scores of greater than three standard deviations above or below the group mean. This procedure revealed no outliers.

Preliminary Analyses

Demographic data are shown in Table 1. Sample ethnicity was mixed with 17 Caucasians (63%), 7 Hispanics (26%), 2 African Americans, (7%), and 1 other (4%). All parent and teacher behavior ratings scale scores were significantly higher for the ADHD group relative to the TD group as expected (see Table 1). Children with ADHD and TD children did not differ on age[4], $t(25)=-2.002$, $p=0.06$, or average Hollingshead (1975) SES scores, $t(25)=-1.956$, $p=0.06$. Although children with ADHD had significantly lower FSIQ scores, $t(25)=-2.083$, $p<0.05$, relative to TD children, the residual FSIQ (see "Method" section) did not differ between groups, $t(25)=0.47$, $p=0.64$. Therefore, the residual FSIQ score was not included in further analyses, and simple model results with no covariates are reported. Means, *SD*s, between-group contrasts, and effect sizes are presented in Table 1.

Tier I: Intercorrelations

Table 2 displays the intercorrelations among group, SSRT, central executive, and PH and VS composite and storage/rehearsal scores. Intercorrelations were computed as a first step to determine whether mediation analyses were warranted. All correlations among variables were significant with four exceptions: PH storage/rehearsal was not significantly correlated with the VS composite, VS storage/rehearsal, or SSRT; and SSD was not significantly correlated with group. PH storage/rehearsal and SSD were therefore excluded from all mediation analyses. Group membership (dummy coded as ADHD = 0, TD = 1) was significantly associated with all other variables, with children with ADHD exhibiting worse performance across SSRT and all working memory measures (i.e., lower WM scores, higher SSRT scores).

Tier II: Test of the Working Memory Model of ADHD

Composite Scores of Working Memory Examination of potential indirect effects with the bootstrap procedure indicated that the VS composite score ($M_\beta = 1.09$, $S.E.=0.42$, 95% CI=0.23 to 1.90) exerted a significant and large magnitude mediation effect on the relationship between the grouping variable (ADHD, TD) and SSRT. The PH composite score, however, was not a significant mediator ($M_\beta = 0.87$, $S.E.=0.52$, 95% CI=−0.12 to 1.90). Standardized beta weights (interpreted as Cohen's *d* effect sizes), *SE*, and 95% confidence intervals for all bootstrap analyses of the indirect effects are displayed in Table 3.

Components of Working Memory Additional analyses were undertaken to determine the extent to which the significant VS mediation effect was attributable to VS storage/rehearsal, central executive, or a combination of both processes. Bootstrap analysis of the indirect effect indicated that the CE ($M_\beta = 1.23$, $S.E.=0.48$, 95% CI=0.21 to 2.14) exerted a significant and large magnitude mediation effect on the relationship between the grouping variable and SSRT. VS storage/rehearsal ($M_\beta = 0.30$, $S.E.=0.29$, 95% CI=−0.24 to 0.90) did not significantly mediate this relationship.

Tier III: Test of the Inhibition Model of ADHD

Composite Scores of Working Memory Examination of potential indirect effects with the bootstrap procedure indicated that SSRT ($M_\beta = -0.31$, $S.E.=0.15$, 95% CI=−0.64 to −0.09) exerted a small magnitude but significant mediation effect on the relationship between the grouping variable and the VS composite score, but not the PH composite score ($M_\beta = -0.25$, $S.E.=0.15$, 95% CI=−0.54 to 0.07).

Components of Working Memory Additional analysis was undertaken to determine which components of working memory are mediated by SSRT. Bootstrap analysis of the indirect effect indicated that SSRT exerted a small magnitude but significant mediation effect on the relationship between the grouping variable and CE ($M_\beta = -0.30$, $S.E.=0.12$, 95% CI=−0.56 to −0.05)[5].

A final set of analyses were undertaken to directly compare the WM and BI models based on their magnitude of mediation effects. Specifically, means and standard errors were used to calculate the *gap* between the lower bound for one variable and the upper bound for another variable. This difference is compared to the pooled SE across variables, with gaps larger than the pooled SE indicating significant differences between models (Cumming and Finch 2005). Results indicated that the mediation effect of CE on SSRT (Cohen's $d=1.23$) was significantly greater than the mediating effect of SSRT on CE (Cohen's $d=0.30$; $p<0.05$). No significant differences were found between the VS Composite/SSRT models. These results suggest that CE exerts a larger magnitude effect on SSRT

[4] All mediation analyses were also completed with age as a covariate. Only the simple models without covariates were reported, however, since the pattern of results did not change.

[5] All mediation analyses were also examined with the conventional method outlined by Baron and Kenney (1986). The overall pattern of results did not change. The VS composite score and CE fully mediated SSRT, while SSRT only partially mediated the VS composite score and CE.

Table 1 Sample and Demographic Variables

Variable	ADHD		Typically Developing		t	d	d_{SE}
	X	*SD*	X	*SD*			
Age	9.27	1.09	10.29	1.53	−2.002†	−0.77	0.40
FSIQ	100.71	14.24	111.46	12.41	−2.083*	−0.80	0.40
SES	44.14	11.85	52.62	10.55	−1.956†	−0.75	0.40
CBCL							
Attention Problems	77.43	10.18	57.54	7.95	5.626***	2.17	0.49
TRF							
Attention Problems	65.00	10.24	54.67	5.71	3.102**	1.23	0.42
CSI-Parent							
ADHD, Combined	76.50	11.27	52.15	13.88	5.02***	1.93	0.47
CSI-Teacher							
ADHD, Combined	63.36	11.06	50.50	8.99	3.215**	1.27	0.42

ADHD attention-deficit/hyperactivity disorder; *CBCL* Child Behavior Checklist; *CSI* Child Symptom Inventory severity *T*-scores; *FSIQ* Full Scale Intelligence Quotient; *SE* standard error; *SES* socioeconomic status; *TRF* Teacher Report Form.

† $p=0.06$, * $p<0.05$, ** $p<0.01$, *** $p<0.001$

than SSRT on CE, but must be considered tentative given the differences in standard errors across models.

Discussion

This is the first study to test opposing predictions stemming from the functional working memory (Rapport et al. 2008b) and behavioral inhibition (Barkley 1997; Sonuga-Barke 2002) models of ADHD by examining the directional relationship between these proposed core deficits. The overall finding that ADHD was associated with significantly slower SSRTs but not SSDs is consistent with findings reported in recent meta-analytic reviews (Alderson et al. 2007; Lijffijt et al. 2005). With few exceptions, examinations of SSRT differences between children with ADHD and typically developing children reveal effect sizes comparable to or greater than most other executive function measures (Willcutt et al. 2005), and have contributed to the conceptualization of behavioral inhibition as a core feature of ADHD (Crosbie et al. 2008). That is, behavioral inhibition is a cognitive function that attenuates the execution of automated-ballistic behavioral responses (i.e., responses to pre-potent stimuli), and is upstream from more complex executive functions such as internalization of speech, self-regulation, working memory, and meta-cognition (Barkley 2006). Evidence from two previous meta-analytic reviews (Alderson et al. 2007; Lijffijt et al. 2005) and a recent experimental study (Alderson et al. 2008), however, indicates that between-group differences in SSRT may reflect an underlying deficit in central executive-controlled focus of attention, which in turn, adversely impacts inhibitory control (Garavan 1998; Oberauer 2003). Central executive attentional focusing requirements for the traditional stop-signal task, for example, require children to sustain attention to go-stimuli to emit correct responses, attend to intermittent auditory tones that signal stopping, and evaluate these competing signals within working memory to determine whether to initiate or withhold/stop a motor response.

Our finding that ADHD is associated with significantly deficient working memory performance is consistent with

Table 2 Zero-order Correlations Among Variables

		1	2	3	4	5	6	7
1.	Group (ADHD/TD)							
2.	VS Composite	−0.83***						
3.	VS storage/rehearsal	−0.62**	0.85***					
4.	PH Composite	−0.82***	0.79***	0.36*				
5.	PH storage/rehearsal	−0.50**	0.26	−0.28	0.78***			
6.	Central executive	−0.85***	0.94***	0.62***	0.95***	0.55***		
7.	SSRT	0.52**	−0.54**	−0.36*	−0.53**	0.28	−0.57***	
8.	SSD	−0.28	0.35*	0.28	0.31	0.13	0.34*	−0.82**

Correlations with group are biserial correlations; *PH* phonological; *SSD* stop-signal delay; *SSRT* stop-signal reaction time; *TD* typically developing; *VS* visuospatial

* $p<0.05$, ** $p<0.01$, *** $p<0.001$

Table 3 Bootstrap Analyses of Indirect Effects

Grouping variable	Mediator variable	Dependent variable	Mean indirect effect (β)	*SE* of mean	95% CI for mean indirect effect
ADHD/TD	PH Composite	SSRT	0.87	0.52	−0.12 to 1.90
ADHD/TD	PH storage/rehearsal	SSRT	0.15	0.23	−0.26 to 0.68
ADHD/TD	VS Composite	SSRT	1.09	0.42	0.23 to 1.90*
ADHD/TD	VS storage/rehearsal	SSRT	0.30	0.29	−0.24 to 0.90
ADHD/TD	CE	SSRT	1.23	0.48	0.21 to 2.14*
ADHD/TD	SSRT	PH Composite	−0.25	0.15	−0.54 to 0.07
ADHD/TD	SSRT	PH storage/rehearsal	−0.11	0.22	−0.56 to 0.36
ADHD/TD	SSRT	VS Composite	−0.31	0.15	−0.64 to −0.09*
ADHD/TD	SSRT	VS storage/rehearsal	−0.24	0.23	−0.77 to 0.15
ADHD/TD	SSRT	CE	−0.30	0.12	−0.56 to −0.05*

ADHD attention-deficit/hyperactivity disorder; *CE* central executive; *PH* phonological; *SSRT* stop-signal reaction time; *TD* typically developing; *VS* visuospatial

*$p<0.05$

findings from past experimental examinations using samples of carefully diagnosed children with ADHD (Martinussen and Tannock 2006; Rapport et al. 2008a). A recent examination of between-group (ADHD, TD) differences in central executive, visuospatial, and phonological working memory processes by Rapport and colleagues (2008a) revealed exceptionally large effect sizes (i.e., Hedges' *g* effect sizes of 2.8, 0.9, and 0.6, respectively) of a magnitude greater than those found for most other executive function tasks used in clinical and laboratory settings (Willcutt et al. 2005), while a second study demonstrated that increased activity in children with ADHD, relative to TD children, is functionally related to demands placed on the working memory system (Rapport et al. 2009). The latter finding regarding the relationship between working memory and activity level is particularly salient to the current study, given that behavioral inhibition models suggest that hyperactivity is a ubiquitous characteristic of ADHD that results from an inability to inhibit responses to task irrelevant stimuli (Barkley 1997).

Mediation analyses were completed to test the predictions stemming from the functional working memory model of ADHD (Rapport et al. 2001). Examination of the independent visuospatial and phonological subsystems—working in tandem with the central executive—revealed that the overall visuospatial system significantly mediated the effect of group membership (ADHD, TD) on stop-signal task performance. The phonological system, however, did not significantly mediate the relationship between group membership and SSRT. These findings are consistent with recent meta-analytic findings of more pronounced deficits in visuospatial working memory processes in ADHD relative to typically developing children (Martinussen et al. 2005), as well as significantly larger between-group effect sizes in stop-signal studies utilizing visuospatial rather than phonological go-stimuli (Alderson et al. 2007). The significant role of the visuospatial but not the phonological system in stop-signal performance initially appears counterintuitive because go-stimuli are presented as text (X, O). The visuospatial system, however, is likely the more efficient modality to process go-stimuli and make choice responses, given the rapid rate at which go-stimuli are presented (one per second). Previous studies of speeded responses suggest that children and adults are able to quickly process and differentiate among text-based information based solely on dissimilar perceptual features (e.g., shape, size; Huang-Pollock et al. 2002). Reliance on the phonological system to process go-stimuli in a typical stop-signal task might therefore slow processing because text-based information must be converted from orthographic to phonological information prior to gaining access to the phonological storage/rehearsal subsystem (Baddeley 2007).

Additional analyses conducted to examine the extent to which the visuospatial mediation effect on behavioral inhibition was attributable to central executive processes alone, or CE processes acting in concert with the VS storage/rehearsal subsystem, revealed that only the central executive significantly mediated the relationship between group membership (ADHD, TD) and stop-signal task performance. The central executive was expected to play a prominent role in the mediating effect between group and SSRT; however, the insignificant contribution of visuospatial storage/rehearsal processing was unanticipated. At least two explanations may account for the findings. First, the significant mediation of SSRT by visuospatial and not phonological working memory is consistent with previous findings demonstrating that the visuospatial system is more strongly correlated with and relies more heavily on central executive processing relative to the phonological system (Alloway et al. 2006; Baddeley 2007). The usual role of the visuospatial subsystem for temporarily storing and rehearsing stop signal visual stimuli may also have been negated because the visual stimuli always appeared in the same location on the computer monitor—a finding consistent with previous research demonstrating minimal VS involvement for stimuli depicted in memorized locations (Awh and Jonides 2001).

Additional analyses were undertaken to directly compare the WM and BI models based on their magnitude of mediation effects. Comparison of standardized beta weights (interpreted as Cohen's *d* effect sizes due to the dichotomous grouping variable) revealed significant differences between models, with the absolute value of the indirect effect of group by CE on SSRT ($\beta=1.23$) more than four times larger than the indirect effect of group by SSRT on CE ($\beta=-0.30$). A nearly identical pattern emerged using the traditional Baron and Kenny (1986) approach to test mediation effects (i.e., CE fully mediated the relationship between the grouping variable and SSRT, while SSRT was only a partial mediator of the relationship between the grouping variable and CE). These findings suggest that behavioral inhibition fails to account for the well documented phonological and visuospatial storage/rehearsal deficits (Martinussen et al. 2005) and only partially accounts for the central executive deficits consistently found in ADHD. Collectively, these finding reveal that large magnitude deficits in the central executive functioning of children with ADHD remain after accounting for behavioral inhibition deficits, and that deficits in behavioral inhibition may be secondary to more complex executive functions such as working memory (Lee et al. 2004).

The unique contribution of the current study was its examination of opposing predictions from inhibition (Barkley 1997; Sonuga-Barke 2002) and functional working memory (Rapport et al. 2001) models of ADHD. Several caveats merit consideration despite methodological refinements such as using the bootstrapping procedure and the latent variable approach to derive measures of VS/PH storage/rehearsal processes and the domain general CE. Generalization of findings from highly controlled laboratory-based experimental investigations to the larger population of children with ADHD is always limited to some extent, and small-*n* studies are at inherent risk for Type II errors. Although the current study utilized a bootstrapping procedure to test each mediator model, which is less vulnerable to Type II errors relative to the conventional Sobel method (Shrout and Bolger 2002), independent experimental replication with larger samples is recommended. Additionally, use of a dual-task procedure that presents WM and BI tasks both independently and simultaneously would allow future studies to experimentally examine the stream of processing without relying on regression analyses. That is, the limited capacity/resource WM and BI systems are expected to differentially interfere with one another when presented simultaneously. Finally, several of the children with ADHD met diagnostic criteria for ODD; however, the degree of comorbidity may be viewed as typical of the ADHD population based on past epidemiological findings (i.e., 59%; Wilens et al. 2002), and recent investigations indicate that ODD does not moderate working memory or SSRT performance in children with ADHD (Klorman et al. 1999; Lijffijt et al. 2005).

The stop-signal paradigm is currently the most commonly used and experimentally sophisticated measure of behavioral inhibition in child psychopathology research. The reliable finding of large magnitude SSRT effects across studies, however, appears to be attributable to ADHD-related differences in working memory. We believe that these findings support the functional working memory model of ADHD, and raise important concerns regarding the central role of behavioral inhibition in extant models of the disorder. In addition, these findings have potentially important clinical implications, and may help explain the inefficacy of cognitive therapies that target symptoms related to impulsivity/behavioral inhibition deficits (Rapport et al. 2001). Interventions that effectively improve identification of underlying core deficits are likely to positively affect secondary symptoms of the disorder, and once developed, may hold considerable promise for promoting long-term treatment gains. For example, initial efforts aimed at promoting working memory function in children with ADHD reported corresponding reduced motor activity (Klingberg et al. 2002). The relative success of future intervention programs, however, will likely reflect the degree to which they target specific underlying WM deficits identified through empirical research.

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