Working Memory Deficits in Boys with Attention-deficit/ Hyperactivity Disorder (ADHD): The Contribution of Central Executive and Subsystem Processes

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Abstract The current study investigated contradictory findings from recent experimental and meta-analytic studies concerning working memory deficits in ADHD. Working memory refers to the cognitive ability to temporarily store and mentally manipulate limited amounts of information for use in guiding behavior. Phonological (verbal) and visuospatial (nonverbal) working memory were assessed across four memory load conditions in 23 boys (12 ADHD, 11 typically developing) using tasks based on Baddeley's (*Working memory, thought, and action*, Oxford University Press, New York, 2007) working memory model. The model posits separate phonological and visuospatial storage and rehearsal components that are controlled by a single attentional controller (CE: central executive). A latent variable approach was used to partial task performance related to three variables of interest: phonological buffer/rehearsal loop, visuospatial buffer/rehearsal loop, and the CE attentional controller. ADHD-related working memory deficits were apparent across all three cognitive systems—with the largest magnitude of deficits apparent in the CE—even after controlling for reading speed, nonverbal visual encoding, age, IQ, and SES.

Keywords ADHD · Working memory · Attention · Attention-deficit/hyperactivity disorder

Contemporary models view working memory as a limited capacity system that enables individuals to briefly store and manipulate information at the forefront of cognition after stimulus configurations responsible for that information expire. This ability serves a critical role in guiding everyday behavior and underlies the capacity to perform complex tasks such as learning, comprehension, reasoning, and planning (Baddeley 2003, 2007). Deficiencies in working memory processes convey moderate to high risk for a broad range of disadvantages and disabilities. For children, these include learning and language disabilities (De Jong 1998; McLean and Hitch 1999), lower academic performance and scholastic achievement (Gathercole et al. 2004; Gathercole et al. 2005), increased rates of internalizing/externalizing problems (Brunnekreff et al. 2007), and social interaction deficits (Alloway et al. 2005).

The working memory construct has assumed a prominent role in theories of executive function during the past decade (Pennington et al. 1996), particularly in nascent models of attention-deficit/hyperactivity disorder (ADHD). Differences among extant models largely reflect whether working memory deficits are hypothesized to play a central or more peripheral role in the phenotypic expression of the disorder. For example, some models consider it a central core component (Rapport et al. 2001, 2007) or candidate endophenotype (Castellanos and Tannock 2002). Others view working memory deficits as one of several executive functions undermined by poorly regulated/underdeveloped behavioral inhibition processes (Barkley 2006), or as one of a constellation of executive function weaknesses that comprise a neurocognitive profile (Willcutt et al. 2005).

Early studies of working memory deficits in children with ADHD yielded mixed results, with some studies reporting significant differences between children with ADHD and typically developing controls, and others failing to replicate these results (for a review, see Pennington and Ozonoff 1996). Many of the methodological confounds

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contributing to these incongruent findings were addressed by two recent meta-analytic reviews. Both appear to provide confirmatory evidence of working memory deficits in children with ADHD relative to typically developing controls, even after controlling for comorbid learning and language disorders (Martinussen et al. 2005) and ADHD-related deficits in overall intelligence and reading achievement (Willcutt et al. 2005). The two reviews categorized tasks as phonological or visuospatial based on Baddeley's (2003) working memory model, whereas Martinussen et al. (2005) alone attempted to quantify the degree to which working memory component processes were dysfunctional.

Baddeley's (2003) model views working memory as a multi-component system consisting of two independent subsystems—phonological (PH) and visuospatial (VS)—that are each equipped with a unique input processor, buffer for the temporary store of modality specific information (PH, VS), and rehearsal mechanism. The central executive provides oversight and coordination of the two subsystems, reacts to changing attentional/multi-task demands, and provides a link between working memory and long-term memory (see Fig. 1). Extensive neuropsychological (Baddeley 2003), neuroanatomical (Smith et al. 1996), neuroimaging (Fassbender and Schweitzer 2006), and factor analytic (Alloway et al. 2006) investigations support

the distinct functioning of the two subsystems and their buffer-rehearsal components. This point is central to our approach for estimating working memory central executive and subsystem processes.

Martinussen et al. (2005) and Willcutt et al. (2005) both reported larger effect sizes for the VS relative to the PH subsystem, with the central executive and buffer/rehearsal components of the two subsystems contributing to the compromised working memory performance observed in children with ADHD (Martinussen et al. 2005). These conclusions may be premature, however, owing to uncontrolled methodological factors in the reviewed studies. For example, the tasks included in the reviews varied considerably with respect to their processing requirements (both within and across studies), and obfuscate comparisons across modality-specific domains that are not equated for difficulty level based on set size and trial parameters. Varying processing demands (i.e., increasing stimulus set size) provides evidence concerning buffer (storage) capacity, and must interact with the grouping variable to confirm buffer/rehearsal deficiencies specific to ADHD.

The methodology employed by Martinussen et al. (2005) to evaluate the central executive and its PH and VS working memory subsystem components also warrants consideration. Forward digits/location and backward dig-
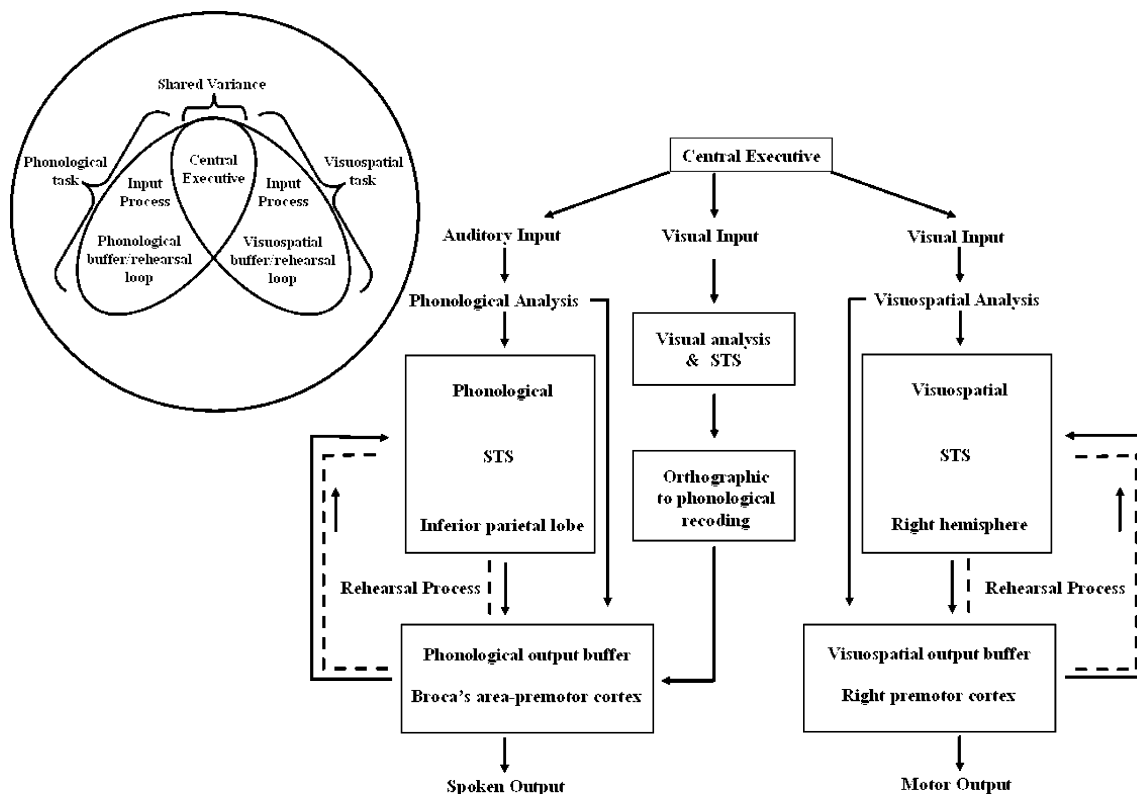
Fig. 1 Adapted and expanded version of Baddeley's (2003) working memory model and associated anatomical loci. The insert shows the component processes related to the phonological (PH) and visuospatial (VS) tasks. STS= short term store. Reprinted and expanded with permission from the author

its/location tasks were used as measures of short-term storage and central executive functioning, respectively, in the meta-analytic review. Digit span tasks (e.g., Digit Span subtest on the WISC-IV) require participants to mentally encode and immediately recall series of verbally or visually presented numbers in the serial order (forward) or reverse serial order (backward) in which they are presented. Location span tasks are intended as nonverbal analogues of digit span tasks, and typically require memory for series of spatial locations. Recent studies by Swanson and Kim (2007) and others (e.g., Colom et al. 2005a, b; Rosen and Engle 1997) provide compelling evidence that forward and backward span tasks load on a single dimension (Swanson et al. 1999) and are both measures of short-term storage—measures of the PH or VS buffer/rehearsal loop rather than central executive processing. Engle, Tuholski, Laughlin, and Conway (1999) have advanced similar arguments and suggest that "a simple transformation of order [from forward to backward] would be insufficient to move a task from the short-term memory storage category to the working memory category" (p. 314).

Because no one task or measure is likely to provide an uncontaminated estimate of central executive functioning due to its multiple functions, cognitive scientists have recently embraced an alternative approach to estimate latent constructs that are hypothesized to be domain-general and upstream from subsidiary processes such as the PH and VS buffer/rehearsal loops. Briefly, this approach calculates a predicted score by regressing the lower-level subsystem processes onto each other based on the assumption that shared variance between the measures (e.g., between the PH and VS tasks) reflects the domain-general, higher-order supervisory mechanism of the two processes. The approach is only valid to the extent that the higher-order central executive is domain-general rather than domain-specific— that is, that there is a single higher-order system or mechanism responsible for the subsidiary systems rather than a separate controller unique to each subsystem. Studies examining Baddeley's (2003) working memory model uniformly support a domain-general central executive (e.g., Alloway et al. 2006) that provides oversight for the distinct PH and VS working memory subsystems (Smith et al. 1996). Contemporary studies have adopted this approach to partition and examine storage (buffer/loop) and processing (central executive) components of working memory using PH buffer/loop and PH buffer/loop + processing tasks (e.g., Colom et al. 2005a, b; Engle et al. 1999; Swanson and Kim 2007), as well as PH and VS working memory tasks (e.g., Kane et al. 2004). The extraction of "common and perfectly reliable variance" (Swanson and Kim 2007, p. 158) between working memory tasks using regression or structural equation model-based techniques has the additional benefit of reducing or eliminating variance related to

non-working memory processes and measurement error (Miyake et al. 2001).[1]

Finally, none of the studies included in either meta-analytic review controlled for potential between-group differences due to PH or VS input processes. Input processes—the mechanisms responsible for encoding PH and VS stimuli for the two subsystems—must be assessed independently to ascertain whether performance problems reflect encoding deficiencies rather than the processes by which encoded information is activated and used by the subsystems' buffer/rehearsal loops (Liberman and Shankweiler 1991). Reading (articulation) and visual scanning speed—two of several tasks traditionally used to index the two subsystem input processes (Bowey et al. 2005)—are used in the current study to address these concerns.

A recent study by Karatekin (2004) addressed the primary shortcomings of the meta-analytic reviews using tasks designed to distinguish between PH and VS working memory and systematically varied stimulus set sizes within the context of Baddeley's (2003) framework. Central executive functioning was assessed using a dual task paradigm that required children to divide their attention concurrently between two tasks. Children with ADHD showed no evidence of differential impairment between PH and VS working memory, or differential impairment as a function of increasing set size and delay relative to control children in the study. They did evidence impairment in central executive functioning relative to controls based on their dual task performance.

The use of recognition rather than recall tasks may account for the non-significant between-group performance differences reported by Karatekin (2004). Despite the moderate dependency between item recognition and cued recall ($r=0.45$ to 0.65 across a wide range of experimental conditions), the tasks require different cognitive processes (Kahana et al. 2005), are associated with different anatomical brain sites (Cabeza et al. 1997), and engender performance differences under identical experimental parameters (MacLeod and Kampe 1996).

Sample attributes—such as the high percentage of ADHD-Inattentive subtype children (nearly 25%) who typically evidence a distinctly different neurocognitive profile (Milich et al. 2001), and normal range parent/teacher ADHD symptom severity rating scores for the ADHD group—may also have influenced the results.

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[1] We acknowledge that some reliable, shared variance may be related to non-central executive shared method factors, as experimental conditions between our two tasks were as identical as possible by design. Based on the converging evidence above, however, we believe that a latent approach to isolating WM components provides a more valid estimate of component processes than the use of any single task.

The present study addresses the primary methodological and sampling issues reviewed above, and examines whether children with ADHD experience deficient working memory processes relative to typically developing children. Our evaluation of children's working memory processes proceeds using a top–down approach. We initially examine potential overall and domain-specific (PH, VS) differences, with planned follow-up analyses to determine whether systematically increasing memory load (set size) differentially affects either of the two subsystems. Each subsystem was examined subsequently to ascertain the extent to which central executive processes and/or specific components (input, buffer/rehearsal processes) account for between-group working memory differences. We hypothesized that children with ADHD would demonstrate impairments across all three working memory domains, with larger magnitude differences found for the CE and VS buffer/loop relative to the PH buffer/loop. We further hypothesized that these differences would be unattenuated or only partially attenuated by age, IQ, SES and potential impairments in visual and phonological encoding rates. No between-group hypotheses were posited regarding the role of increasing memory load on performance.

Method

Participants

The sample was comprised of twenty-three male children aged 8 to 12 years (M=9.04, SD=1.36), recruited by or referred to the Children's Learning Clinic–IV (CLC-IV) through community resources (e.g., pediatricians, community mental health clinics, school system personnel, self-referral). The CLC-IV is a research-practitioner training clinic known to the surrounding community for conducting developmental and clinical child research and providing pro bono comprehensive diagnostic and psychoeducational services. Its client base consists of children with suspected learning, behavioral or emotional problems, as well as typically developing children 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 (TD) without a psychological disorder. All parents and children gave their informed consent/assent to participate in the study, and IRB approval was obtained 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 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, and test–retest reliability of 0.63 to 1.00 (Kaufman et al. 1997).

Twelve children met the following criteria and were included in the ADHD group: (1) an independent diagnosis by the CLC-IV's directing clinical psychologist using DSM-IV criteria for ADHD based on K-SADS interview with parent and child; (2) parent ratings of at least 2 SDs above the mean on the Attention Problems clinical syndrome 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 Problems clinical syndrome 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 CSI requires parents and teachers to rate children's behavioral and emotional problems based on DSM-IV criteria using a 4-point Likert scale. The CBCL, TRF, and CSI are among the most widely used behavior rating scales for assessing psychopathology in children. Their psychometric properties are well established (Rapport et al. 2007). All children in the ADHD group met criteria for ADHD-Combined Type, and six were comorbid for Oppositional Defiant Disorder (ODD).

Eleven 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) maternal rating below 1.5 SDs on the clinical syndrome scales of the CBCL and TRF; and (4) parent and teacher ratings within the non-clinical range on all CSI subscales. Typically developing children were actively recruited through contact with neighborhood and community schools, family friends of referred children, and other community resources.

Children that presented with (a) gross neurological, sensory, or motor impairment, (b) history of a seizure disorder, (c) psychosis, or (d) Full Scale IQ score less than 85 were excluded from the study. None of the children were receiving medication during the study—seven 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.

Statistical/Methodological Overview and Measures

Statistical/Methodological Overview As reviewed previously, the PH and VS systems are functionally and

Table 1 Sample and demographic variables

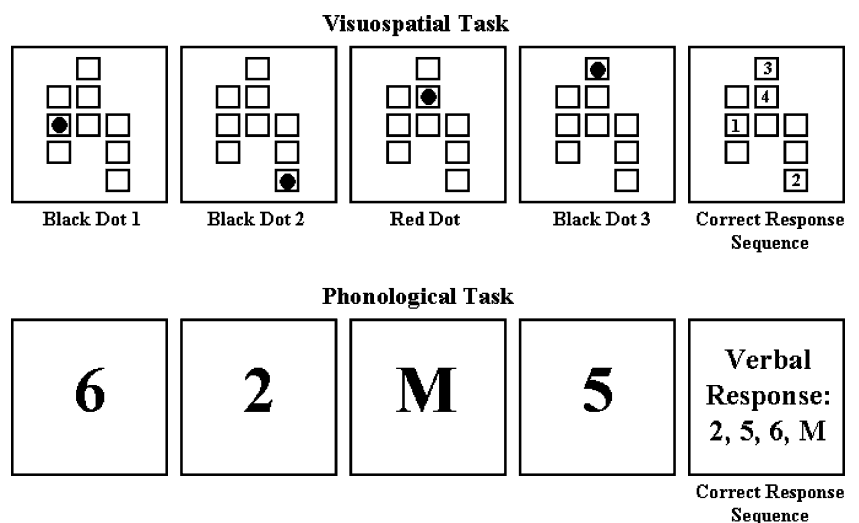| Variable	ADHD		TD Children		
	$\overline{X}$	SD	$\overline{X}$	SD	F (1,21)
Age	8.75	1.29	9.36	1.43	1.17
FSIQ	100.92	15.22	110.18	13.11	2.43
SES	43.46	12.25	52.50	7.57	6.13*
CBCL					
Attention Problems	78.50	10.53	55.64	7.06	36.68***
TRF					
Attention Problems	66.25	8.83	48.73	16.92	9.94**
CSI-Parent					
ADHD, Combined	77.75	9.92	48.73	11.11	9.29**
CSI-Teacher					
ADHD, Combined	63.08	11.05	49.50	9.57	43.83***
Reading Speed	2.94	1.48	5.20	0.63	21.89***
Symbol Search	0.16	0.04	0.20	0.05	3.96†

ADHD Attention deficit/hyperactivity disorder–combined type; *CBCL* Child Behavior Checklist; *CSI* Child Symptom Inventory–symptom severity *T*-scores; *FSIQ* Full Scale Intelligence; *Reading Speed* words per second; *SES* Socioeconomic Status; *Symbol Search* items per second; *TD* typically developing children; *TRF* Teacher Report Form
† $p=0.06$
*$p \leq 0.05$
**$p \leq 0.01$
***$p \leq 0.001$

anatomically independent, with the exception of a shared (domain-general) central executive controller (Baddeley 2003) that is upstream from and provides oversight and coordination for the two subsidiary working memory systems. Statistical regression techniques were consequently employed to provide reliable estimates of the controlling central executive and its subsidiary PH and VS systems through a related series of calculations. Briefly, the central executive was estimated by regressing the lower-level subsystem processes onto each other based on the assumption that shared variance between the two measures (PH, VS) reflects the domain-general, higher-order supervisory mechanism for the two processes. The two predictor scores were subsequently averaged to provide an estimate of the central executive as described below. Removing the common variance of the PH and VS subsidiary systems has the additional advantage of providing residual estimates of PH and VS functioning independent of central executive influences. Precedence for using shared variance to statistically derive central executive and/or buffer/loop variables is found for working memory components in Colom et al. (2005a, b), Engle et al. (1999), Kane et al. (2004), Rosen and Engle (1997), and Swanson and Kim (2007).

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 (see Fig. 2), and to indicate the 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.

Fig. 2 Visual schematics of the visuospatial (*top*) and phonological (*bottom*) tasks

Visuospatial Task

Black Dot 1   Black Dot 2   Red Dot   Black Dot 3   Correct Response Sequence

Phonological Task

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

Correct Response Sequence

Children were seated approximately 0.66 m from the computer monitor. The task was presented in four counterbalanced set size blocks (i.e., 3, 4, 5, or 6 stimuli), with each set size consisting of 24 trials. Children were administered a five trial practice block consisting of 3 stimuli immediately prior to the set size three experimental condition until achieving a minimum of 80% correct. A practice block of four stimuli was used for experimental conditions with set sizes of 4, 5, and 6 stimuli. Children who failed to obtain a minimum of 80% correct across the five practice trials of 4 stimuli were readministered the 3 stimuli practice trials, followed by another administration of the 4 stimuli practice trials, until achieving the 80% correct criteria.

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 phonological working memory based on Baddeley's (2003) 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 blinded to diagnostic status were shielded from the participant's view and independently recorded oral responses (interrater reliability=95.6% agreement). The PH task was presented in four counterbalanced set size blocks (i.e., 3, 4, 5, or 6 stimuli), with each set size consisting of 24 trials.

Children were administered a five trial practice block consisting of 3 stimuli immediately prior to the set size 3 experimental condition until achieving a minimum of 80% correct. A practice block of 4 stimuli was used for experimental conditions with set sizes of 4, 5, and 6 stimuli. Children who failed to obtain a minimum of 80% correct across the five practice trials were readministered the 3 stimuli practice trials, followed by another administration of the 4 stimuli practice trials, until achieving the 80% correct criteria.

VS Dependent Variables The number of stimuli correct 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 buffer/rehearsal loop). Composite VS scores were computed by averaging each child's score across set sizes to address questions concerning overall working memory differences among groups. The VS buffer/loop was estimated based on the preceding statistical/methodological rationale using the following procedures. PH scores were covaried from VS scores at each set size to remove common variance associated with the domain-general central executive. These four VS buffer/loop scores were then averaged to provide an overall estimate of the contribution of the VS buffer/loop to performance on the VS task independent of shared CE influences (see Fig. 1 inset).

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

Reading Speed (RS) The RS task provided an index of children's ability to rapidly encode, process, and articulate visually presented words. Children read a 203-word passage (adapted from a beginning second grade reading text) presented on a computer monitor immediately after responding to the *Press Spacebar to Begin* written instruction, and re-pressed the spacebar when they reached the last word on the page (END). Total story words (203) were divided by the passage reading time to calculate reading speed (words per second).

Visuospatial Encoding Scores from the Symbol Search B subtest of the WISC-III (Wechsler 1991) or WISC-IV (Wechsler 2003) provide an index of how rapidly children

process, encode, and distinguish unfamiliar visual symbols. Children were presented 2 target stimuli on the left side of the page and instructed to determine whether either target was present in a search group of 5 stimuli on the right side of the page. Children were instructed to work as quickly as possible without making mistakes, and allowed 120-s to respond by marking *Yes* or *No* for each item with a pencil. Raw scores were computed by subtracting the number of incorrect responses from total responses, allowing for a maximum raw score of 60. Visuospatial encoding was defined as raw score divided by task duration (i.e., symbols per second).

Procedures

The VS, PH, and RS tasks were programmed using Superlab Pro 2.0 (2002). All children participated in four consecutive Saturday assessment sessions at the CLC-IV. The VS, PH, and RS tasks were administered as part of a larger battery of laboratory tasks that required the child's presence for approximately 2.5 h per session. Frequent breaks ranging between 5 and 15 min were scheduled between tasks to minimize fatigue. Each child was administered four VS and four PH conditions (i.e., 3, 4, 5, and 6 VS and PH set sizes) across the four testing sessions. The eight working memory conditions were counterbalanced to control for order effects. Tasks were administered by trained graduate assistants whom were not blind to participant diagnosis; however, written instructions were standardized for all tasks and presented verbatim, and data was collected by blinded coders (PH) or computer (VS, RS).

Results

Data Screening

Power Analysis GPower software version 3.0.5 (Faul et al. 2007) was used to determine needed sample size using an ES of 0.70 based on the average magnitude of ADHD PH and VS deficits reported by Martinussen et al. (2005). Power was set to 0.80 as recommended by Cohen (1992). For an ES of 0.70, $\alpha=0.05$, power $(1-\beta)=0.80$, 2 groups, and four repetitions (i.e., set sizes), 20 total subjects are needed for a repeated measures ANOVA to detect differences and reliably reject H_0.

Outliers Each of the four tasks (visuospatial, phonological, reading speed, and Symbol Search) was screened for univariate outliers (i.e., ≥ 3.5 SD above or below group mean). A score corresponding to 3.5 SD above the ADHD group mean was substituted for one ADHD child's reading speed score as a result.

Preliminary Analyses Demographic data are shown in Table 1. Sample ethnicity was mixed with 16 Caucasians (69%), 5 Hispanics (22%), and 2 African Americans (9%). 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 typically developing children did not differ on age, $F(1,21)=2.34$, $p=0.14$, or intelligence, $F(1,21)=2.43$, $p=0.13$. Univariate ANOVAs revealed significant between-group differences in Reading Speed, $F(1,21)=21.89$, $p<0.0005$, and SES, $F(1,21)=6.31$, $p=0.02$. On average, children with ADHD read slower and had lower Hollingshead (1975) SES scores than TD children. Symbol Search group differences were non-significant at $F(1,21)=3.96$, $p=0.06$. Reading Speed, Symbol Search, FSIQ, age, and SES were not significant covariates of any of the Tier I, II, or III analyses (all $p\geq 0.18$). We therefore report the simple model results with no covariates. Means, SDs, and F values are presented in Tables 2 and 3.

Tier I: Composite Scores

The first level of analysis examined overall differences among working memory systems (phonological, visuospa-

Table 2 Phonological and visuospatial correct stimuli per trial composite scores

	Phonological $\overline{X}$ (SD)	Visuospatial $\overline{X}$ (SD)	Composite $\overline{X}$ (SE)	Task $F(1,21)$	Contrasts
ADHD	2.36 (0.61)	1.33 (0.44)	1.85 (0.13)		
TD	3.77 (0.34)	3.07 (0.69)	3.43 (0.14)		
Composite	3.03 (0.87)	2.17 (1.05)	–	59.00*	VS < PH
Group $F(1,21)$			66.32*		
Contrasts			ADHD < TD		

System × group interaction, $p=0.16$, *ns*

ADHD Attention deficit/hyperactivity disorder; *PH* phonological task; *TD* typically developing children; *VS* visuospatial task

*$p<0.001$

Table 3 Phonological and visuospatial set size analyses

	Phonological set size[a]					Set size F (3,63)	Set size contrasts	Visuospatial set size[b]					Set size F (3,60)	Set size contrasts
	3	4	5	6	Group composite			3	4	5	6	Group composite		
	$\overline{X}$ (SD)	$\overline{X}$ (SD)	$\overline{X}$ (SD)	$\overline{X}$ (SD)	$\overline{X}$ (SE)			$\overline{X}$ (SD)	$\overline{X}$ (SD)	$\overline{X}$ (SD)	$\overline{X}$ (SD)	$\overline{X}$ (SE)		
ADHD	2.35 (0.47)	2.87 (0.74)	2.48 (1.09)	1.73 (1.00)	2.36 (0.14)	5.50**	6<4,5; 3<4	1.44 (0.57)	1.61 (0.72)	1.25 (0.68)	1.03 (0.19)	1.33 (0.17)	9.16**	6<3=4; 5= 3,4,6
TD	2.89 (0.11)	3.67 (0.24)	4.31 (0.52)	4.22 (0.77)	3.77 (0.15)	29.80***	3<4<5=6	2.60 (0.67)	3.43 (0.38)	3.43 (1.36)	3.04 (1.11)	3.12 (0.18)	2.89†	3<4=5=6
Set Size Composite	2.61 (0.44)	3.26 (0.68)	3.36 (1.26)	2.92 (1.55)	–	8.28***	3<4,5; 6<5	1.97 (0.84)	2.44 (1.10)	2.24 (1.50)	1.94 (1.26)	–	3.73*	3,6<4,5=3,4,6
Group F[c]	13.36***	11.94***	25.52***	44.35***	46.21***			21.13***	54.34***	22.24***	38.37***	52.87***		
Group Contrasts	A<T	A<T	A<T	A<T	A<T			A<T	A<T	A<T	A<T	A<T		

A=ADHD, T or TD=typically developing children

[a] Phonological group x set size interaction, F (3,63)=14.32, p<0.0005

[b] Visuospatial group x set size interaction, F (3,60)=3.11, p=0.03

[c] Phonological df(1,21); visuospatial df(1,20)

† p=0.054

* p<0.05

** p≤0.01

*** p≤0.001

tial) and groups (ADHD and TD children). Results are depicted in Table 2 and Fig. 3a. A Mixed-model ANOVA indicated significant main effects for working memory system ($p<0.0005$) and group ($p<0.0005$). Phonological performance was significantly better than visuospatial performance across groups, and children with ADHD performed significantly worse than TD children across tasks. The system by group interaction was not significant ($p=0.16$).

Tier II: Set Size

The second level of analysis examined the effect of increasing set size on phonological and visuospatial working memory performance across groups. All results, including F values, p values, and degrees of freedom, are shown in Table 3. Using Wilk's criterion, a significant one-way MANOVA on phonological and visuospatial trials correct (set sizes 3, 4, 5, and 6 for both systems) by group (ADHD and TD) confirmed the relationship between the two subsystems and overall working memory differences among the two groups, Wilks' $\lambda=0.18$, $F(8,13)=7.34$, $p=0.001$. Mixed-model ANOVAs with LSD post hoc tests were conducted separately for phonological and visuospatial stimuli correct to further explicate this result.

Phonological ANOVA For phonological stimuli correct, the Mixed-model ANOVA was significant for group ($p<0.0005$) and set size ($p<0.0005$). Children with ADHD performed significantly worse than TD children. The post hoc test for set size is reported in Table 3. The group by set size interaction was significant ($p<0.0005$). LSD post hoc tests for the interaction revealed that children with ADHD performed significantly worse across all set sizes compared to TD children (all $p<0.003$); however, the pattern of performance differed between the groups. For typically developing children, the mean number of stimuli correct per trial increased with each increase in set size from 3 to 5 (all $p\leq0.001$), and remained constant from set size 5 to 6 ($p=0.57$). TD children performed significantly better on set size 6 compared to set sizes 3 and 4 (both $p\leq0.03$). ADHD children also recalled more stimuli under set size 4 relative to set size 3 ($p=0.004$). Unlike TD children, however, their recall performance began to decline under higher set size conditions, and declined significantly from set sizes 4 and 5 to set size 6 (both $p=0.01$). Their performance on set sizes 3 and 6 did not differ significantly ($p=0.07$). Hedges' g effect size indicated that the magnitude difference between children with ADHD and typically developing children was 1.89 standard deviation units (95% CI=0.80–0.98). Results are depicted in Fig. 3b.

Visuospatial ANOVA For visuospatial stimuli correct, the Mixed-model ANOVA was significant for group ($p<$
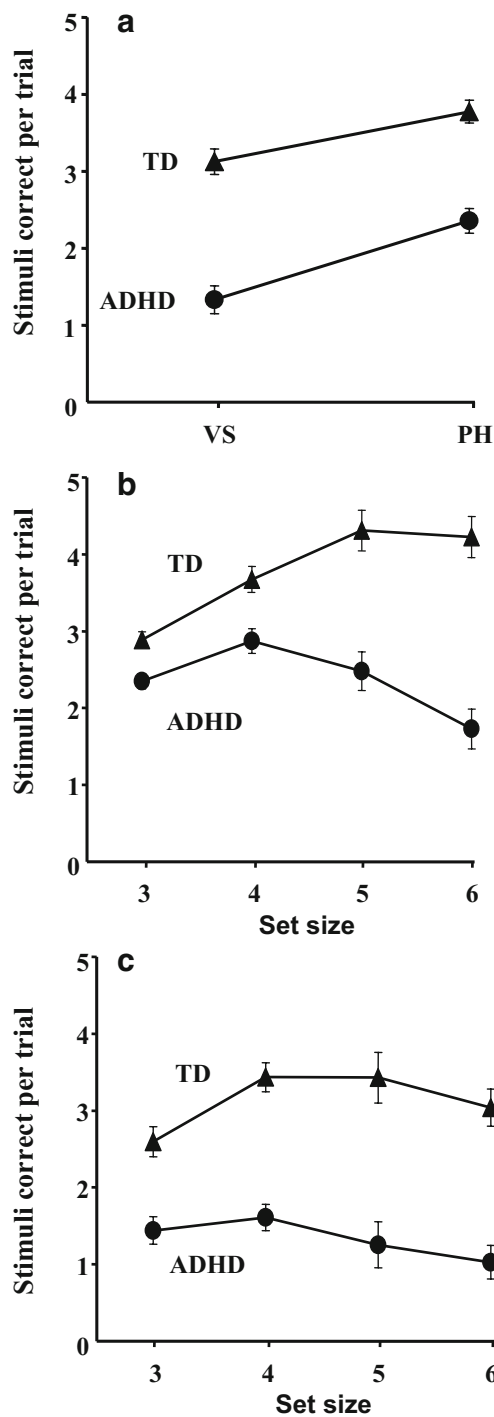
Fig. 3 a Number of stimuli correct as a function of working memory system (phonological=PH; visuospatial=VS) and group; Number of **b** phonological and **c** visuospatial stimuli correct as a function of set size and group: typically developing children (*triangles*) and ADHD children (*circles*). *Vertical bars* represent standard error

0.0005), set size (*p*=0.03), and the group by set size interaction (*p*=0.03). Children with ADHD performed significantly worse than TD children. The post hoc test for set size is reported in Table 3. LSD post hoc tests for the interaction revealed that children with ADHD performed

significantly worse across all set sizes compared to TD children (all *p*<0.0005); however, the performance patterns for the two groups was appreciably different. For typically developing children, the mean number of stimuli correct per trial increased from set size 3 to 4 (*p*<0.0005), and then remained constant among set sizes 4, 5, and 6 (all *p*>0.06). In contrast, children with ADHD failed to improve between set sizes 3 and 4 (*p*=0.37), and evinced a significant decline in performance on set size 6 compared to set sizes 3 and 4 (both *p*<0.02). Set sizes 5 and 6 did not differ (*p*=0.19). Hedges' *g* effect size indicated that the magnitude difference between children with ADHD and typically developing children was 2.31 standard deviation units (95% CI= 2.19–2.41). Results are depicted in Fig. 3c.

Tier III: Components of Working Memory

Additional analyses were undertaken to determine whether the group differences found above were attributable to one or more working memory components (central executive, phonological or visuospatial buffer/loop) based on the supporting literature and statistical/methodological rationale provided previously.

Phonological Buffer/Loop PH buffer/loop performance was estimated by covarying VS scores out of PH scores at each set size to remove common variance associated with the domain-general central executive. These four PH buffer/loop scores were then averaged to provide an overall estimate of the contribution of the PH buffer/loop to performance on the PH task. An independent samples *t*-test on the derived variable indicated significant between-group differences in buffer/loop performance, $t(21)=-2.19$, $p=0.04$, with TD children evincing higher levels of PH buffer/loop contribution to task performance. Hedges'*g* effect size indicated that the magnitude difference between children with ADHD and typically developing children was 0.55 standard deviation units (95% CI=0.51–0.59).

Visuospatial Buffer/Loop PH composite scores were covaried from VS composite scores at each set size to remove common variance associated with the domain-general central executive. These four VS buffer/loop scores were then averaged to provide an overall estimate of the contribution of the VS buffer/loop to performance on the VS task. An independent samples *t*-test on the derived variable indicated significant between-group differences in buffer/loop performance, $t(21)=-3.38$, $p=0.003$, with TD children evincing higher levels of VS buffer/loop contribution to task performance. Hedges' *g* effect size indicated that the magnitude difference between children with ADHD and typically developing children was 0.89 standard deviation units (95% CI=0.80–0.98).

Central Executive The independent samples *t*-test on the derived central executive score was significant, $t(21) = -8.06$, $p < 0.0005$—children with ADHD exhibited central executive deficits relative to TD children. Hedges' *g* effect size indicated that the magnitude difference between children with ADHD and typically developing children was 2.76 standard deviation units (95% CI=2.64–2.88).

Discussion

The current study examined overall, domain-general (central executive), and subsidiary (PH, VS storage/rehearsal loop) working memory processes in children with ADHD-Combined Type relative to typically developing (TD) children. Overall, PH working memory abilities were significantly better developed relative to VS abilities in this sample of 8–12 year olds regardless of group membership. This finding is consistent with developmental studies that suggest a fundamental transformation in children's use of working memory, moving from primarily visual encoding to a combined visual–verbal strategy, to finally the adult-like reliance on the phonological subsystem (Palmer 2000; Pickering 2001).

Examination of the two independent subsystems (PH, VS)—working in tandem with the central executive controller—revealed that each subsidiary system was significantly deficient in children with ADHD relative to typically developing children of similar age and intelligence. These deficiencies were apparent under even the lowest stimulus set size conditions, and became more pronounced under higher memory load conditions. The magnitude of between-group differences for the two subsystems—ranging from 1.89 to 2.31 standard deviations for the PH and VS subsystem, respectively—was considerably higher than estimates reported in previous meta-analytic reviews (Martinussen et al. 2005; Willcutt et al. 2005). These discrepancies likely reflect two sources of methodological differences between the previous reviews and current study. Effect size estimates of PH and VS subsystem functioning in both reviews were based on an amalgamation of findings reported for forward and backward digit/location span tasks that varied considerably with respect to task type, task demands (e.g., number of trials), and stimulus set size parameters (memory load). Controlling for these factors and using a greater number of trials to assess recall performance was expected to reduce variability and maximize between-group differences if they existed. The more obvious source of the between-study ES differences reflects the different methodological approaches used to estimate central executive and subsystem functioning reviewed earlier. Specifically, the ES estimates in the current study reflect the central executive

working in concert with the PH and VS buffer/rehearsal loop components, whereas previous estimates represent the PH and VS buffer/rehearsal components alone (Colom et al. 2005a, b; Rosen and Engle 1997; Swanson et al. 1999). After removing variance in each of the subsystems attributable to the central executive, the PH (0.55) and VS (0.89) effect size estimates in this study were quite similar to (i.e., PH, VS ES=0.52 and 0.96, respectively), and within the confidence intervals of, those reported by Martinussen et al. (2005).

The significant group by set size interactions for the two working memory subsystems obligated a closer examination of children's PH and VS recall performance under the four memory load conditions. Typically developing children showed initial gains in both subsystems as set size increased from 3 to 4 stimuli, and either recalled additional stimuli (PH) or maintained their level of recall performance (VS) under the higher (5, 6) stimulus set size conditions. In contrast, the PH and VS recall performance of children with ADHD peaked under the four set size condition, and declined under higher set size conditions. The ADHD group's VS subsystem recall never exceeded 1.61 stimuli on average, and significantly deteriorated under high set size conditions. Collectively, these results suggest an underlying impairment in the buffer (storage)/rehearsal loop functioning in both subsystems, as well as possible differences in the use of metamemory strategies to maintain gains under higher set size conditions (Siklos and Kerns 2004; Voelker et al. 1989). Systematically increasing the number of stimuli to be recalled will eventually overwhelm even an intact working memory system, and conscious strategies must be employed to optimize recall under these circumstances.

Parsing the central executive's shared contribution to the PH and VS subsystems revealed several interesting findings. The magnitude of group differences associated with the two subsidiary systems was substantially diminished after removing common variance attributable to the central executive (ES reduced from 1.89 to 0.55, and from 2.31 to 0.89 for the PH and VS subsystems, respectively), and indicate a more dysfunctional VS relative to PH subsystem in children with ADHD based on the non-overlapping confidence intervals. The difference in central executive functioning between the two groups was remarkable (ES= 2.76), and highlights the critical role played by the central executive in directing and focusing attention, while providing the necessary oversight and coordination for the two subsidiary systems in addition to integrating working memory and long-term memory. These abilities are clearly impaired in children with ADHD. The moderately larger proportion of variance attributable to central executive functioning in the VS relative to the PH subsystem is also consistent with recent findings by Alloway et al. (2006), who found that central executive functioning contributed

substantially more to the VS than PH subsystem in 7- to 11-year-old children. The finding that both systems remained impaired after removing the central executive's contribution provided additional confirmation of PH and VS buffer/loop processing deficiencies in ADHD.

Examination of PH and VS input processes were examined to determine whether either of these components accounted for the ADHD performance deficits. Slowed articulation rate can limit buffer capacity (Henry and Millar 1993), but did not moderate the significant between-group differences in PH working memory despite the robust correlation ($r=0.591$, $p<0.001$) between the two measures. The use of numbers and letters in the PH task—juxtaposed with the buffer's ability to hold up to 2-s of information and ADHD children's three-word/second reading ability—may have limited any negative impact associated with slowed articulation rate (Baddeley 2007).

Collectively, our results corroborate and extend the findings reported in recent meta-analytic reviews (Martinussen et al. 2005; Willcutt et al. 2005) in finding comparatively larger deficits for the VS relative to the PH subsidiary subsystem, but are contradictory to those reported by Karatekin (2004), who found no significant PH or VS deficits in children with ADHD relative to controls. The inconsistency between the results may be due to the more clinically impaired nature of our sample, but more likely reflects the inherent differences between recall and recognition tasks discussed earlier (Cabeza et al. 1997; Kahana et al. 2005), and a probable rehearsal/reordering masking effect associated with displaying target stimuli during response trials.

The unique contribution of the current study was its systematic examination of central executive, PH and VS working memory component processes in children with ADHD relative to typically developing children across a wide range of memory load conditions while controlling for differences in PH/VS input processes, intelligence, age, and SES. Several caveats merit consideration despite these methodological refinements. Generalization of findings from highly controlled, laboratory-based experimental investigations with stringent inclusion criteria to the larger population of children with ADHD is always limited to some extent, and independent experimental replication with larger samples that include females, older children, and other ADHD subtypes is recommended. Our cell sizes were nevertheless sufficient based on the a priori power analysis conducted for PH and VS working memory variables. Given our stringent inclusion criteria, it is possible that the children with ADHD in the current study represent a more severe ADHD group than may be found in typical community or clinic settings (Gjone et al. 1996). However, diagnoses were confirmed using gold standard assessment procedures to ensure the integrity of our grouping variable,

and cross-informant consistency in symptom severity was needed due to the moderate sensitivity and specificity of available rating scales (Rapport et al. 2007). Although extensive effort was expended to equate the phonological and visuospatial paradigms in terms of cognitive load, directions, and number of trials, differences in performance across tasks may not be attributable entirely to modality differences. The results, however, were consistent with past studies demonstrating better developed phonological than visuospatial abilities in elementary-aged children (Alloway et al. 2006). 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 recent epidemiological findings (i.e., 59%; Wilens et al. 2002), and recent investigations indicate that working memory deficiencies observed in ADHD are independent of ODD (Klorman et al. 1999). Additional studies including children with clinical disorders other than ODD are needed to determine the specificity of working memory deficits in ADHD. Finally, reading speed was not a particularly useful measure of phonological processing ability (also, see Bowey et al. 2005), and future studies may need to employ more sensitive measures such as alphanumeric naming speed when using number–letter reordering sequences as working memory tasks.

The current results have both applied and heuristic implications for the field, assuming the findings generalize to the larger population of affected children. Impaired central executive processing and PH/VS buffer/rehearsal loop deficits likely disrupt basic learning processes, as well as the incremental acquisition of skill and knowledge obtained in educational settings that are highly dependent on working memory (Alloway et al. 2005). The association between working memory functioning and academic achievement is well established (Aronen et al. 2005; Gathercole et al. 2004, 2005; Swanson and Howell 2001), and may reflect ADHD-related developmental delays in cortical maturation of prefrontal cerebral regions related to working memory, attention, and motor planning (Shaw et al. 2007). The resultant culmination of disrupted learning processes likely contributes to longitudinal findings of poor school performance, significant scholastic underachievement, and low high school graduation rates characteristic of ADHD (Barkley et al. 2006; Mannuzza et al. 1993). Additional research is needed to examine which elements of working memory are associated with specific academic skill deficits and other symptoms in ADHD in anticipation of designing proactive interventions to enhance working memory performance. A clearer understanding of the central executive's function and interaction with the two subsidiary systems and long-term memory are also warranted given its robust contribution to working memory deficiencies in ADHD.

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