

Understanding Phonological Memory Deficits in Boys with Attention-Deficit/Hyperactivity Disorder (ADHD): Dissociation of Short-term Storage and Articulatory Rehearsal Processes

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Abstract The current study dissociated and examined the two primary components of the phonological working memory subsystem—the short-term store and articulatory rehearsal mechanism—in boys with ADHD ($n=18$) relative to typically developing boys ($n=15$). Word lists of increasing length (2, 4, and 6 words per trial) were presented to and recalled by children following a brief (3 s) interval to assess their phonological short-term storage capacity. Children's ability to utilize the articulatory rehearsal mechanism to actively maintain information in the phonological short-term store was assessed using word lists at their established memory span but with extended rehearsal times (12 s and 21 s delays). Results indicate that both phonological short-term storage capacity and articulatory rehearsal are impaired or underdeveloped to a significant extent in boys with ADHD relative to typically developing boys, even after controlling for age, SES, IQ, and reading speed. Larger magnitude deficits, however, were apparent in short-term storage capacity ($ES=1.15$ to 1.98) relative to articulatory rehearsal ($ES=0.47$ to 1.02). These findings are consistent with previous reports of deficient phonological short-term memory in boys with ADHD, and suggest that future attempts to develop remedial cognitive interventions for children with ADHD will need to include active components that require children to hold increasingly more information over longer time intervals.

Keywords ADHD · Phonological working memory · Articulatory rehearsal processes · Phonological recall

ADHD is a complex, chronic, highly heritable, and potentially debilitating disorder of brain, behavior, and development that affects between 3% and 7% of school-age children (APA 2000). Accumulating evidence suggests that the core symptoms of ADHD—inattentiveness, impulsivity, and hyperactivity—are associated with underdeveloped/dysfunctional cerebellar-striatal/adrenergic-prefrontal circuitry (Castellanos 2001; Shaw et al. 2007) and are hypothesized to reflect the outcome of dysfunction in one or more executive functions (Barkley 1997; Rapport et al. 2008b; Sonuga-Barke et al. 2010; Willcutt et al. 2005). For example, meta-analytic reviews (Martinussen et al. 2005; Willcutt et al. 2005) and experimental investigations are highly consistent in documenting working memory deficits in children with ADHD relative to typically developing children, even after controlling for differences in intelligence, age, and socioeconomic status (Martinussen and Tannock 2006; Rapport et al. 2008b). Experimental studies also have demonstrated that working memory deficits are related functionally to two of the three core features of ADHD—viz., inattention (Kofler et al. 2010) and hyperactivity (Rapport et al. 2009)—and may underlie behavioral inhibition deficits associated with the disorder (Alderson et al. 2010). These findings may reflect delayed cortical maturation in distinct brain regions associated with working memory (Shaw et al. 2007) and provide a compelling impetus for investigating distinct working memory processes and potential capacity limitations in children with ADHD.

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Working memory is a limited capacity system that enables individuals to process information drawn from short-term and long-term memory (Baddeley 2007). Among the various models of working memory (Cowan 2005; Conway and Engle 1996; Engle 2002; Kane et al. 2001; Oberauer and Kliegl 2006), Baddeley's multi-component model is particularly well suited for examining working memory deficits in children with ADHD due to its empirically validated domain-general and subcomponent processes, extensive neuroanatomical support, and receptivity to empirical scrutiny (Baddeley 2007). The primary components of Baddeley's (2007) working memory model are the domain-general central executive and the phonological and visuospatial storage/rehearsal subsystems.¹ The domain-general central executive is responsible for coordinating the two subsystems, focusing and dividing attention, and interacting with long-term memory. The phonological and visuospatial storage/rehearsal subsystems are responsible for temporarily holding modality-specific information in the forefront of cognition for use in guiding behavior, and reflect the *memory* components of working memory (Baddeley 2007). The phonological subsystem stores verbal, speech-based information such as numbers and words, whereas the visuospatial subsystem provides this function for spatial information and abstract visual stimuli that cannot be encoded phonologically. The distinct functioning of the domain-general central executive, the two storage subsystems (visuospatial, phonological), and their associated rehearsal components, is supported by extensive evidence derived from neuropsychological (Baddeley 2003), neuroanatomical (Luck et al. 2009; Smith et al. 1996), neuroimaging (Fassbender and Schweitzer 2006), and factor analytic (Alloway et al. 2006) investigations.

Meta-analytic reviews (Martinussen et al. 2005; Willcutt et al. 2005) have uniformly reported significant deficits in phonological storage/rehearsal processes in children with ADHD relative to typically developing children. This discovery is of particular importance due to the established contribution of phonological storage/rehearsal to reading and math performance (Gathercole et al. 2006; Swanson and Kim 2007), word recognition skills (Swanson and Howell 2001), and reading comprehension in children (Cain et al. 2004). Findings from an experimental study, however, suggest that phonological storage deficits may reflect the presence of comorbid reading and language impairments rather than ADHD-related phonological storage deficiencies (Martinussen and Tannock 2006). This conclusion was based on finding significant digits backward but not digits

forward performance deficits for children with ADHD relative to typically developing children, whereas children with ADHD with comorbid reading and language disabilities exhibited performance deficits on both tasks. Studies by Rosen and Engle (1997) and others (e.g., Colom et al. 2005; Swanson and Kim 2007), however, provide compelling evidence that forward and backward span tasks (e.g., digits forward and backward) load on a distinct short-term memory dimension and separately from established working memory measures (Swanson et al. 1999). Forward and backward simple span tasks also differentially predict multiple academic domains relative to established working memory measures (e.g., Swanson and Kim 2007), whereas working memory complex span but not forward/backwards simple span measures predict fluid intelligence after accounting for their shared variance (Engle et al. 1999). Thus, consensus in the cognitive literature is that performance on both forward and backward simple span tasks reflect short-term storage/rehearsal rather than central executive processes, and that additional rehearsal demands associated with "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" (Engle et al. 1999, p. 314). Martinussen and Tannock's (2006) finding of significant ADHD-related performance deficits on the digits backward task is thus consistent with the meta-analytic reviews and supports the accumulating evidence of phonological storage/rehearsal deficits in children with ADHD. The study, nevertheless, highlights the importance of controlling for differences in phonological short-term storage deficits in studies examining reading and language disabilities in children with ADHD. In addition, the moderately larger effect size on one measure of phonological storage/rehearsal (digits backward) relative to another measure of the same construct (digits forward) in the Martinussen and Tannock (2006) study may imply that the two tasks, despite their similarities and shared factor loading as indicators of phonological short-term storage/rehearsal, place different demands on the rehearsal subcomponent of the phonological subsystem. This hypothesis highlights the need to dissociate phonological storage from rehearsal processes to examine the extent to which specific subcomponents are implicated in ADHD as discussed below.

The phonological subsystem has two distinct subcomponents: a short-term store and an articulatory rehearsal mechanism. The phonological short-term store is limited both in terms of capacity and duration of information stored. It can hold a developmentally-dependent quantity of auditory-based information for approximately three seconds, at which time the information can be prepared for spoken output or be maintained in the short-term store for an extended time period by engaging in (subvocal) rehearsal. The

¹ A third storage component—viz., the episodic buffer—has been proposed recently to explain the integration of information from multiple cognitive systems, but is currently considered a "conceptual tool" (Baddeley 2007, p. 149) rather than a formal component of the model.

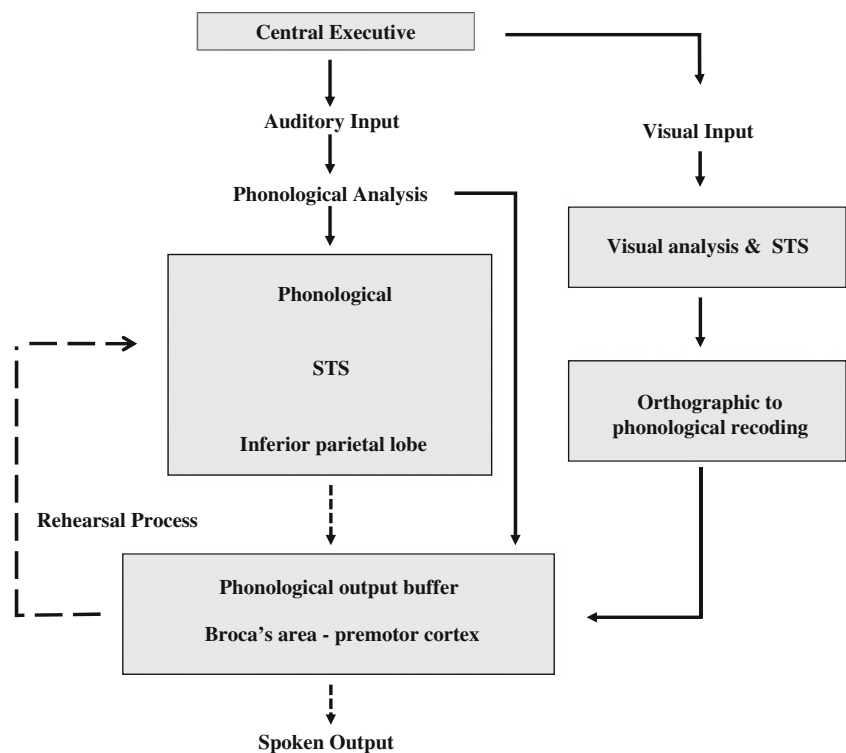
phonological subsystem consists also of two encoding mechanisms (auditory, visual) and a spoken output buffer (Fig. 1). Information encoded through the auditory input channel gains automatic access to the phonological short-term store, whereas information encoded through the visual input channel must be converted from orthographic to phonological code prior to entry into the phonological subsystem (Baddeley 2007). Deficiencies associated with the phonological working memory subsystem in children with ADHD, however, likely reflect deficits/developmental delays in the short-term storage and/or rehearsal mechanism, rather than encoding or spoken output mechanisms. This supposition is based on the failure of previous investigations to find encoding (Sergeant and Scholten 1985) or spoken output (Douglas and Benezra 1990; Gibson et al. 2010) deficits in children with ADHD, as well as the observation that most studies reporting ADHD-related phonological deficits have used an auditory stimulus presentation and oral response format, eliminating the need for orthographic-to-phonological conversion and overt motor responses.

Despite the highly uniform findings of phonological storage/rehearsal deficits in children with ADHD (see Martinussen et al. 2005 for a meta-analytic review), no study to date has dissociated the phonological subsystem's two primary components—the short-term store and articulatory rehearsal mechanism. This is surprising given compelling evidence of their distinct neuropsychological functions, neuroanatomical locations, and developmental trajectories. Specifically, the phonological short-term store

is associated with the left parietal cortex (Awh et al. 1996; Jonides et al. 1998) and begins to develop at age two (Garon et al. 2008). It is expected to reach maturity by age 12 (Cowan et al. 2010; Tillman et al. 2011), at which time children are able to hold an adult-like 4 ± 1 chunks of information (Cowan 2001). In contrast, the articulatory rehearsal mechanism facilitates the (subvocal) rehearsal of information to be replenished and preserved in the short-term store and is associated with functioning in the left prefrontal region (i.e., Broca's area; Awh et al. 1996; Paulesu et al. 1993; Smith and Jonides 1999a). The speed and proficiency of covert rehearsal both undergo considerable maturation between six and twelve years of age (Kail and Ferrer 2007).

Extant neuropsychological evidence reveals that impairments can occur in one or both phonological subsystem components and result in unique clinical presentations (Shallice and Butterworth 1977; Vallar and Baddeley 1984; Vallar et al. 1997; Vallar and Shallice 1990). For example, phonological storage deficits hinder the development of language acquisition, reading comprehension, and story recall, whereas rehearsal deficits are associated with phonemic awareness impairment, create a bottle-neck in the short-term store, and in doing so, impede the ability to process information quickly. Dissociation of these components thus represents an essential step in examining whether one or both components contribute to the phonological deficits observed in children with ADHD and may provide guidance for developing distinct cognitive interventions for these children. For example, several current cognitive

Fig. 1 Adapted and expanded version of Baddeley's (2007) phonological working memory subsystem and associated anatomical loci. *STS* short-term store. Reprinted and expanded with permission from the author



interventions for children with ADHD target primarily short-term storage capacity, with only incidental training of rehearsal processes. The presence of significant rehearsal deficits in children with ADHD would inform translational research and highlight the importance of adopting active components that require children to hold information for progressively longer time intervals.

The aim of the present study was to dissociate the phonological storage and rehearsal subsystem components to investigate the extent to which previous findings of ADHD-related impairments reflect deficient functioning of the short-term store, the articulatory rehearsal mechanism, or both. Word lists of increasing length (2, 4, and 6 words) were presented to and recalled by children following a brief (3 s) interval to assess their phonological short-term storage capacity. A 3 s interval was selected to mirror the estimated time duration that phonological information (e.g., words) can be held in short-term memory without rehearsal (Baddeley 2007). Percent of stimuli recalled was examined to determine each child's verbal span, defined as the maximum set size at which a child recalls at least 50% of stimuli correctly as recommended by Conway et al. (2005). Children's ability to utilize the articulatory rehearsal mechanism to actively maintain information in the phonological short-term store was assessed using word lists at their established span but with extended rehearsal times (12 s and 21 s delays). Children with ADHD were hypothesized to exhibit deficient short-term storage based on a meta-analytic review that relied on digit span as an index of storage capacity (Martinussen et al. 2005). A deficient articulatory rehearsal mechanism also was expected because (a) children with ADHD exhibit a slower overt articulation rate relative to typically developing children (Rappoport et al. 2008b; Rucklidge and Tannock 2002), which predicts decreased articulatory rehearsal proficiency (Hitch et al. 1989), and (b) the larger backward relative to forward digit span task effect sizes reported previously (e.g., Martinussen and Tannock 2006) were hypothesized to reflect increased rehearsal demands.

Method

Participants

The sample consisted of 33 boys aged 8 to 12 years 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 is a research-practitioner training clinic known to the surrounding community for conducting developmental and clinical child research and providing *pro bono* comprehensive diagnostic and psychoeducational

services. Its client base consists of children with suspected learning, behavioral or emotional problems, as well as typically developing children (those without a suspected psychological disorder) whose parents agree to have them participate in developmental/clinical research studies. A psychoeducational evaluation was provided to the parents of all participants.

Two groups of children participated in the study: children with ADHD and typically developing children without a psychological disorder. 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). The K-SADS assesses onset, course, duration, severity, and impairment of current and past episodes of psychopathology in children and adolescents based on DSM-IV criteria. Its psychometric properties are well established, including interrater agreement of 0.93 to 1.00, test-retest reliability of 0.63 to 1.00, and concurrent (criterion) validity between the K-SADS and psychometrically established parent rating scales (Kaufman et al. 1997).

Eighteen children met the following criteria and were included in the ADHD-Combined Type group: (1) an independent diagnosis by the CLC-IV's directing clinical psychologist using DSM-IV criteria for ADHD-Combined Type based on K-SADS interview with parent and child which assesses symptom presence and severity across home and school settings; (2) parent ratings of at least 2 *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 (Rappoport et al. 2008b). None of the children in the ADHD group were

comorbid for any disorders with the exception of ODD (44%).

Fifteen children met the following criteria and were included in the typically developing group: (1) no evidence of any clinical disorder based on parent and child K-SADS interview; (2) normal developmental history by maternal report; (3) ratings below 1.5 *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 recruited through contact with neighborhood and community schools, family friends of referred children, and other community resources.

Children presenting with (a) gross neurological, sensory, or motor impairment, (b) history of a seizure disorder, (c) psychosis, or (d) Full Scale IQ score less than 85 were excluded from the study. None of the children received medication during the study. Nine had received psychostimulant trials previously or were prescribed psychostimulants currently but withheld medication for a minimum of 24 h prior to each testing session.

Measures/Methodological Overview

Measures

Phonological Memory Task A phonological memory task was created for the present study to assess verbal short-term memory based on Baddeley's (2007) model. Children were instructed to recall lists of monosyllabic words selected from a second grade reading list and reviewed by the clinic's research team. Words with strong emotional content (e.g., death), homonyms (e.g., eight and ate), and proper nouns (e.g., Mike) were excluded from the list. Each word from the final list of 756 words was assigned randomly to one of nine word lists that each consisted of 21 distinct trials. All words were recorded using AT&T Natural Voices[®] Text-to-Speech speech synthesis system and presented auditorily at three distinct set size conditions (2, 4, and 6 words) and three distinct delay conditions (3 s, 12 s, and 21 s). No words were re-used across the nine set size and delay conditions (3 set sizes \times 3 delay conditions each). The words were presented at 1 s intervals. A red light appeared after the presentation of each trial and was displayed for 3 s, 12 s, or 21 s depending on the delay condition. Word list presentation and response instructions were identical across all conditions to rule out phonological input (auditory) and output (spoken) mechanisms as potential explanations for changes in performance across conditions. In addition, auditory presentation was selected because auditory information gains automatic access to the phonological storage system (Baddeley 2007), thus ensuring that all children's phonological subsystems were engaged during the task. Spoken output was selected to avoid confounding our findings with

ADHD-related motor output deficits (e.g., Klein et al. 2006) given that spoken (left prefrontal) and motor output (right premotor) rely on neuroanatomically distinct cortical regions (Baddeley 2007).

The brief 3 s delay condition was utilized to minimize the reliance on echoic memory (the brief sensory registry for holding acoustic information). The two extended delay conditions were selected to equate the delay interval between adjacent conditions (i.e., 9 s intervals between 3 s and 12 s, and between 12 s and 21 s) and allow sufficient time to challenge the articulatory (subvocal) rehearsal mechanism based on earlier findings demonstrating that children are able to maintain words by means of covert rehearsal up to 30 s (Bauer 1977). All 21 trials in a given condition contained the same number of words and delay duration. A green light appeared at the conclusion of the imposed time delay. Children were instructed to recall as many words as they could remember from the presented list following the onset of the green light. A bell chimed after the response phase, indicating that a new word list was to be presented (intertrial interval = 1 s). Two trained research assistants, shielded from the participant's view and blind to diagnostic status, recorded oral responses independently. Interrater reliability was computed for all nine conditions for all children, and was 97.7%. External validity for the phonological memory task used in the study was evidenced by its expected magnitude relationship with an established, verbally presented measure of short-term memory (WISC-III or -IV Digit Span standard score: $r = 0.66$), coupled with the expected declining pattern of correlations with increasing time delay (i.e., $r = 0.56$ and 0.52 for the 12 s and 21 s delay conditions, respectively); all p values ≤ 0.005 .

Reading Speed The Reading Speed task provided an approximation of children's covert articulatory speed, which can impact covert rehearsal proficiency (Hitch et al. 1989). Faster subvocal rehearsal is associated with maintaining more items in the short-term store for a longer duration (Baddeley 2007). This metric must be considered an inexact approximation, however, given its reliance on orthographic-to-phonological conversion. Children read a 203-word passage adapted from a second grade reading text (Johns 1988) presented visually on a computer monitor immediately after responding to the "Press Spacebar to Begin" written instruction, and were instructed to re-press the spacebar when they reached the last word on the page (END). The story words (203) were divided by the passage reading time to calculate words read per second as an indicator of reading speed.

Intelligence All children were administered either the Wechsler Intelligence Scale for Children third edition (Wechsler 1991) or fourth edition (Wechsler 2003) to obtain

an overall estimate of intellectual functioning. The change-over to the fourth edition was due to its release during the conduct of the study and to provide parents with the most up-to-date intellectual evaluation possible. The Full Scale Intelligence Quotient (FSIQ) was not analyzed as a covariate because it shares significant variance with phonological memory and would result in removing substantial variance associated with phonological memory from phonological memory (Ackerman et al. 2005). Instead, a residual FSIQ score was derived using a latent variable approach. A composite phonological score was created by averaging the phonological memory performance variables and removing its shared variance from FSIQ. The residual FSIQ score (FSIQ_{res}) represents IQ that is unrelated to estimated phonological memory functioning and was examined to evaluate between-group differences in intellectual functioning.

Procedures

The Phonological Memory and Reading Speed tasks were programmed using Superlab Pro 2.0 (2002). All children participated in four consecutive Saturday assessment sessions. The tasks were administered as part of a larger battery of neurocognitive tasks that require the child's presence for approximately 2.5 h per session. Children completed all tasks while seated alone in an assessment room. Performance was monitored at all times by the examiner, who was stationed just out of the child's view to provide a structured setting while minimizing the previously reported performance improvements associated with examiner demand characteristics (Gomez and Sanson 1994; Power 1992). 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 Phonological Memory task at three set size conditions and three time delay conditions (2 words at 3 s, 12 s, and 21 s delays, 4 words at 3 s, 12 s, and 21 s delays, and 6 words at 3 s, 12 s, and 21 s delays) across the four testing sessions. Administration of the nine phonological memory tasks was counterbalanced to control for order effects with the exception that all three delay conditions at a particular set size were administered on the same day. The order of delay condition administration within each day was counterbalanced to control for practice effects. Children were seated in a caster-wheel swivel chair approximately 0.66 m from the computer monitor for all tasks. Children were administered a practice block consisting of two stimuli per trial immediately prior to the phonological memory conditions until achieving a minimum of 80% correct.

Phonological Memory Dependent Variables The average number of stimuli recalled correctly per trial for the three

set size conditions (2, 4, and 6 words) at the 3 s delay conditions served as the primary dependent variable for assessing children's phonological storage capacity while concurrently limiting the need to actively rehearse the information. Phonological information held in the phonological short-term store must be rehearsed after approximately three seconds to refresh the memory trace (Baddeley 2007). To assess children's ability to utilize the articulatory rehearsal mechanism to maintain information in the phonological store, each child was set at their individual phonological span (2, 4, or 6 words per trial \times 21 trials each at 12 s and 21 s delay conditions). Phonological span was defined as the maximum set size (2, 4, or 6 words per trial) at which a child recalls at least 50% of the stimuli correctly during the 3 s delay conditions as recommended by Conway et al. (2005). All children received 21 unique trials at each delay condition (12 s, 21 s) regardless of the number of words per trial. Performance across the delay conditions was analyzed using a percent correct metric due to individual differences in the number of words presented per trial.

Results

Data Screening

Outliers All variables were screened for univariate/multivariate outliers and tested against $p < 0.001$. No outliers were identified.

Preliminary Analyses

Power Analysis An average Hedges' g effect size (ES) of 0.48 was calculated based on two studies providing phonological storage means and SD s for children with ADHD and typically developing (TD) children (Martinussen et al. 2005; Rapport et al. 2008a). GPower software version 3.1 (Faul et al. 2007) was used to determine needed sample size using this ES , with power set at 0.80 as recommended by Cohen (1992). For an ES of 0.48, $\alpha = 0.05$, power $(1 - \beta) = 0.80$, 2 groups, and three repetitions (phonological set sizes 2, 4, 6; 3 s, 12 s, and 21 s delay conditions), 30 total participants are needed for a repeated measures ANOVA to detect differences and reject reliably the H_0 . Thirty-three children were included in the current study.

Demographic data are shown in Table 1. Sample race/ethnicity was mixed with 19 Caucasian/Non-Hispanic (58%), 7 Hispanic or Latino (21%), 2 African American, (6%), and 5 multiracial/ethnic children (15%). 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 significantly on Hollingshead (1975) SES

Table 1 Sample and demographic variables

Variable	ADHD		Typically Developing		<i>F</i>
	\bar{X}	<i>SD</i>	\bar{X}	<i>SD</i>	
Age	9.30	1.12	10.15	1.43	3.68
FSIQ	101.44	13.74	111.73	11.52	5.30*
SES	45.58	11.53	52.93	9.95	3.76
CBCL					
AD/HD Problems	71.33	7.45	56.20	8.72	28.98***
TRF					
AD/HD Problems	65.94	8.12	54.93	5.02	20.87***
CSI-Parent					
ADHD, Combined	75.11	12.23	51.53	12.99	28.76***
CSI-Teacher					
ADHD, Combined	63.56	10.45	51.07	8.15	14.20***
Reading Speed	3.65	1.93	5.48	1.01	10.77**

ADHD attention-deficit/hyperactivity disorder; CBCL Child Behavior Checklist *T*-scores; CSI Child Symptom Inventory severity *T*-scores; FSIQ Full Scale Intelligence Quotient; SES socioeconomic status; TRF Teacher Report Form *T*-scores. Reading Speed = words per second
* $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$

scores ($p=0.06$), age ($p=0.06$), or FSIQ_{res} ($p=0.72$). We therefore report simple model results with no covariates.² Mean, *SD*s, and *F* values are presented in Table 1.

Test of the Phonological Short-Term Store

A 2 (ADHD, TD) \times 3 (set sizes 2, 4, 6) Mixed-model ANOVA was conducted to examine phonological stimuli recalled correctly across the 3 s delay set sizes. The results are shown in Table 2 and Fig. 2a and revealed significant effects for group, set size, and the group by set size interaction (all $p < 0.001$). LSD post hoc tests revealed that children with ADHD performed significantly worse across all set size conditions relative to TD children (all $p \leq 0.002$); however, the pattern of performance differed between the groups. The main effect for set size for the ADHD group was nonsignificant ($p=0.08$), indicating that the mean number of phonological stimuli recalled correctly per trial did not differ across the three set size conditions for children with ADHD. In contrast, the performance of TD children increased significantly from set size 2 to 4 ($p < 0.001$), and remained stable across the set size 4 and 6 conditions ($p=0.37$). Computation of Hedges' *g* indicated that the

² Age and SES were tested as potential covariates given the trend toward between-group differences. Their inclusion did not change the overall pattern of results.

average magnitude difference between children with ADHD and TD children was 1.65 standard deviation units (range=1.15 to 1.98).

An additional analysis was conducted to examine group differences in phonological capacity, defined as the maximum set size at which a child recalls at least 50% of the stimuli correctly as recommended by Conway et al. (2005). The number of participants with a maximum span of 2, 4, and 6 words was computed separately for each group and subjected to a χ^2 analysis. Results indicated that children with ADHD were significantly more likely than typically developing children to have maximum spans of 2 (35% vs. 0%) or 4 words (53% vs. 27%), and significantly less likely to have a maximum span of 6 words (12% vs. 73%), $\chi^2(1, 33)=15.01$, $p < 0.01$, $\Phi=0.67$.³ Collectively, these results indicate that children with ADHD display significantly decreased phonological storage capacity relative to typically developing children, even under conditions with minimal rehearsal demands.

Test of the Articulatory Rehearsal Mechanism

The ensuing analyses examined whether the phonological rehearsal mechanism is also impaired in children with ADHD, independent of their storage capacity deficits. This was accomplished by setting each child at their individual phonological span (defined in the previous paragraph) and examining changes in performance associated with increased delay (i.e., 12 s and 21 s delay conditions relative to the 3 s delay). Percentage of stimuli correct per trial was used instead of number correct because different numbers of stimuli per trial were presented to each child based on their individual storage capacity. All children received 21 unique trials at each delay condition (3 s, 12 s, 21 s) regardless of the number of words presented per trial. Results of the 2 (ADHD, TD) \times 3 (3 s, 12 s, 21 s delayed recall conditions) Mixed-model ANOVA are shown in Table 3 and Fig. 2b and revealed a significant main effect for delay condition ($p < 0.001$), no significant main effect for group ($p=0.22$), and a significant group by delay condition interaction ($p < 0.001$). Computation of Hedges' *g* indicated that the average magnitude difference between children with ADHD and TD children was 0.71 standard deviation units during the 12 s and 21 s delay conditions ($ES=0.47$ and 1.02, respectively). LSD post hoc tests for the interaction revealed that the performance of children with ADHD and TD children was not statistically different under the 3 s and 12 s recall conditions (both $p \geq 0.23$); however, the percentage of

³ Data for one participant in the ADHD group was excluded because he was unable to recall $\geq 50\%$ of the stimuli at the lowest set size condition (set size 2, 3 s delay). This child was excluded also from the articulatory rehearsal mechanism analyses.

Table 2 Phonological short-term store

	Phonological Set Size (3 s Delay Interval) ^a				<i>F</i>	Set Size Contrasts
	2-word \bar{X} (SD)	4-word \bar{X} (SD)	6-word \bar{X} (SD)	Group Composite \bar{X} (SE)		
ADHD	1.75 (0.25)	2.18 (0.92)	1.95 (0.83)	1.96 (0.14)	2.78	2=4=6
TD	1.97 (0.04)	3.53 (0.34)	3.41 (0.56)	2.97 (0.07)	106.60***	2<4=6
Set Size Composite	1.85 (0.22)	2.79 (0.99)	2.62 (1.03)	–	43.97***	2<4=6
Group <i>F</i>	11.20**	28.67***	33.64***	38.11***		
Group Contrasts	ADHD < TD	ADHD < TD	ADHD < TD	ADHD < TD		
Hedges' <i>g</i> Effect Size	1.15	1.83	1.98			
95% CI	0.42 to 1.87	1.03 to 2.63	1.16 to 2.80			

ADHD attention-deficit/hyperactivity disorder; CI confidence interval; TD typically developing; ** $p \leq 0.01$; *** $p \leq 0.001$

^a Short-term storage group by set size interaction, $F(2, 62) = 18.52$, $p < 0.001$

phonological stimuli recalled correctly was significantly higher for the TD children relative to children with ADHD under the 21 s recall condition ($p = 0.007$).

Relative to themselves, TD children recalled significantly fewer words during the 12 s relative to 3 s condition (6 percentage point decrease; $p = 0.03$; $ES = 0.41$), but their performance did not decrease significantly from the 12 s to 21 s delay conditions (4 percentage point decrease; $p = 0.06$; $ES = 0.23$). In contrast, the percentage of words recalled correctly for children with ADHD decreased significantly and more substantially from the 3 s to 12 s delay (18 percentage point decrease; $p < .001$; $ES = 1.08$), and further decreased from the 12 s to 21 s delay conditions (12 percentage point decrease; $p = 0.002$; $ES = 0.79$). Overall, the impact of delay was modest for typically developing children (10 total percentage point decrease; $ES = 0.62$), but substantial for children with ADHD (30 percentage point decrease; $ES = 2.08$) such that the magnitude of ADHD-related phonological recall impairments relative to typically developing children increased by approximately 0.5 *SD* every nine seconds (Table 3). Collectively, these findings indicate that all children experience a significant performance decline when required to maintain information in phonological memory over time; however, children with ADHD show a disproportionately greater rate of information loss over an identical time period, even after accounting for their decreased overall storage capacity.

Impact of Subvocal Rehearsal on Phonological Storage/Rehearsal Performance

A final set of analyses were conducted using Reading Speed to examine the impact of subvocal rehearsal abilities on the phonological storage and rehearsal deficits identified in the current study. Children with ADHD read significantly slower than TD children, $F(1, 29) = 10.51$, $p = 0.003$.

Reading Speed was not a significant covariate of any of the analyses (all p values ≥ 0.05), and its inclusion did not change the interpretation of any results.

Discussion

Previous experimental studies and meta-analytic reviews have implicated deficient phonological short-term storage as part of a more generalized working memory deficit in children with ADHD (Martinussen et al. 2005; Rapport et al. 2008a; Sowerby et al. 2011). These deficiencies may reflect an inability to retain an age appropriate quantity of encoded phonological information in the short-term memory store, impairments in covert rehearsal and maintenance of stored information over brief time intervals, or deficiencies in both processes. This study is the first to dissociate and examine the two primary components of the phonological working memory subsystem—the short-term store and articulatory rehearsal mechanism—in children with ADHD relative to typically developing children. The results indicate that phonological short-term storage capacity is impaired or underdeveloped to a significant extent in children with ADHD relative to typically developing children, even after controlling for age, SES, IQ, reading speed, and input and spoken output mechanisms. Large magnitude between-group differences were apparent under even the lowest (2-word) storage capacity condition ($ES = 1.15$), and increased substantially under the 4- and 6- word conditions (i.e., $ES = 1.83$ and 1.98 , respectively). The larger effect size metrics reflect the ADHD's group inability to store more than 2.2 words on average under any of the capacity load conditions, whereas typically developing children were able to recall 3.5 words on average under high load conditions (i.e., 62% to 75% greater capacity). These results are consistent with findings demonstrating that left parietal and other regions

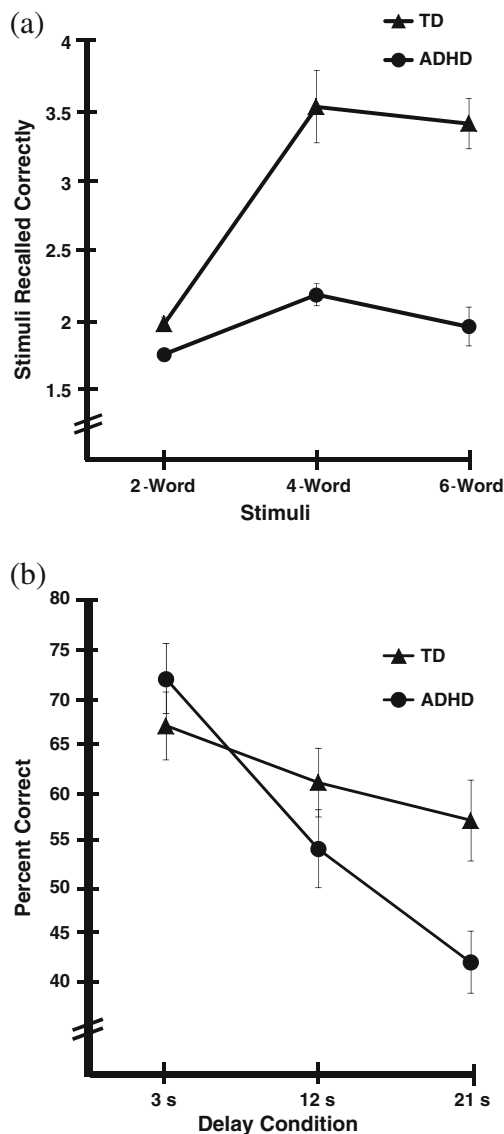


Fig. 2 **a** Average number of stimuli correct under the 2-, 4-, and 6-word recall conditions (3 s delay); **b** percentage of words recalled correctly under the two delayed recall conditions (12 s, 21 s) relative to the 3 s condition based on each child's pre-established phonological storage span. Error bars reflect standard error

associated with the temporary storage of phonological information (Awh et al. 1996; Jonides et al. 1998; Smith and Jonides 1999b) are delayed developmentally in children with ADHD by 2 to 3 years relative to typically developing children (Shaw et al. 2007).

Our findings are consistent with the most recent meta-analytic review analyzing phonological short-term memory differences between children with ADHD and typically developing children, with the exception that our between-group effects were considerably larger than the 0.48 effect size reported by Martinussen and colleagues (2005). The larger magnitude differences likely reflect methodological differences between the studies used in the meta-analytic

review and the current study. The most critical of these differences is the procedure for examining short-term phonological memory capacity. Nearly all of the effect size estimates in the review were derived from simple span tests (e.g., digit span) that conventionally use a limited number of trials (usually two) to determine the longest list of single digit numbers children can recall correctly, coupled with a discontinuation rule that terminates the assessment once short-term memory capacity is established. Using a greater number of trials (21 versus 2) to assess recall performance at each memory load and requiring children to complete all three memory load conditions regardless of whether they exceeded capacity was expected to reduce variability and maximize between-group differences based on recent studies incorporating similar methodology (e.g., Alderson et al. 2010; Rapport et al. 2008a). A final factor that may have contributed to the between-study effect size differences is the type of stimuli encoded and recalled verbally. The use of over-learned stimuli, such as the single digit numbers used in the meta-analytic review, may be chunked into smaller bits of information and recalled more easily than the unrelated words used in the current study (e.g., the digits 2, 7, 4, 3 can be chunked into 27 and 43 so that two rather than four pieces of information are held in short-term memory).

The results of the present investigation are discrepant with past (Douglas and Benezra 1990) and recent (Gibson et al. 2010) investigations that reported intact short-term phonological recall in children with ADHD using supraspan tasks. The discrepant results likely reflect differences in underlying memory processes and attentional resources required by supraspan tasks relative to word recall tasks involving shorter word lists. For example, supraspan tasks require children to learn as many words as possible from extended word lists (i.e., usually 12 or more words per trial). In addition, the visual and combined visual-auditory versions of these tasks used by Gibson et al. (2010) and Douglas and Benezra (1990), respectively, required children to read and encode each word in the extended list, convert the information to phonological code as they proceed through the word list (required for auditory output during the recall stage), and simultaneously rehearse previously stored words covertly to maintain them in the short-term phonological store. A suppression effect for recalling words is observed typically under these conditions due to the inherent dual processing demands (i.e., reading and encoding new words interferes with the rehearsal and maintenance of previously stored words), weakening the typically developing children's recall performance and making it more similar to the ADHD group's performance. As a result, any benefit resulting from typically developing children's larger storage capacities and better functioning rehearsal mechanisms would be suppressed. In contrast, the 2-, 4-,

Table 3 Articulatory Rehearsal Mechanism

	Delayed Recall Conditions (% Recalled) ^a				<i>F</i>	Recall Contrasts
	3 s Delay \bar{X} (SD)	12 s Delay \bar{X} (SD)	21 s Delay \bar{X} (SD)	Group Composite \bar{X} (SE)		
ADHD	71.71 (15.14)	54.01 (16.85)	41.64 (13.81)	55.80 (3.00)	30.12***	3>12>21
TD	66.67 (13.95)	60.75 (13.84)	57.19 (16.60)	61.50 (3.60)	7.89**	3>12=21
Recall Composite	69.35 (14.59)	57.17 (15.65)	48.93 (16.88)	–	35.41***	3 >12>21
Group <i>F</i>	0.95	1.50	8.37**	1.52		
Group Contrasts	ADHD = TD	ADHD = TD	ADHD < TD	ADHD = TD		
Hedges' <i>g</i> Effect Size	–0.09	0.47	1.02			
95% CI	–.76 to 0.58	–0.21 to 1.15	0.31 to 1.73			

ADHD attention-deficit/hyperactivity disorder; CI confidence interval; TD typically developing; ** $p \leq 0.01$; *** $p \leq 0.001$

^a Articulatory rehearsal mechanism group by recall condition interaction, $F(2, 60) = 9.55$, $p < 0.001$

and 6-word length lists in the current study were presented to children orally, bypassing the orthographic-to-phonological conversion process and associated suppression effects. Comparing our results with those reported by Gibson et al. (2010) lend tentative support to this interpretation. In the current study, children with ADHD and typically developing children were able to recall up to 2.2 and 3.5 words on average, respectively, compared to the 2.5 words recalled on average by both ADHD and typically developing adolescents in the Gibson et al. (2010) study. That is, both groups in the Gibson et al. (2010) study recalled a similar number of words as our ADHD group despite being 4 years older on average (13 years of age), an age at which the phonological store is expected to have matured fully in typically developing children (Tillman et al. 2011).

The second phase of the study examined whether the phonological rehearsal mechanism, working in tandem with the short-term store, is impaired or underdeveloped in children with ADHD relative to typically developing children. This was accomplished by establishing the phonological span capacity for each child (Conway et al. 2005), then examining the number of words maintained in the phonological store over extended 12 s and 21 s delay intervals. These results were consistent with extant research indicating that all children recall fewer words when rehearsal is required to maintain information in the phonological short-term store over an extended time interval (Cowan 2001); however, the pattern of decline differed considerably between the two groups. Typically developing children experienced an initial 6% decline in performance under the 12 s delay relative to 3 s delay condition, and an additional 4% decline between the 12 s and 21 s conditions (10% overall decline; ES = 0.62). In contrast, children with ADHD experienced a more acute drop-off in performance under the 12 s delay condition (18%), and an additional 12% decline between the 12 s and 21 s conditions (30% overall decline;

ES = 2.08). As a result, the magnitude of between-group differences increased by approximately 0.5 SD with each additional nine seconds of delay. These findings are consistent with longitudinal MRI findings of ADHD-related developmental delay in left pre-frontal regions associated with Broca's area (Shaw et al. 2007) that are implicated in the covert rehearsal of phonological information for purposes of maintaining it in the short-term store (Awh et al. 1996; Smith and Jonides 1999b).

The current results are consistent with ADHD etiological models hypothesizing impaired phonological short-term storage and rehearsal as part of a more generalized working memory deficit (Barkley 1997; Rapport et al. 2008b). Our finding that ADHD-related recall deficits increased substantially across the delay conditions appears consistent also with predictions from the dual pathway model, which proposes that ADHD-related impairments in tolerating delay represent one pathway through which ADHD symptoms manifest behaviorally (Sonuga-Barke et al. 2010). However, delay aversion is an unlikely candidate to explain the overall pattern of results in the current study given that manipulating the number of stimuli to be recalled over a brief (3 s) delay had a much larger magnitude impact on between group differences than manipulating the delay duration (i.e., storage effect sizes of 1.15 to 1.98, relative to rehearsal effect sizes of 0.47 to 1.02). This conclusion is consistent also with the surprising number of failures to replicate delay aversion deficits in ADHD (e.g., Karalunas and Huang-Pollock 2011; Schweitzer and Sulzer-Azaroff 1995; Solanto et al. 2007; Tripp and Alsop 2001), combined with previous findings that children with ADHD do not evince increased delay aversion relative to their unaffected peers during tasks such as those used in the current study that do not allow the child to control task duration (Sonuga-Barke et al. 1992). We hypothesize that delay aversion, if present in ADHD, reflects an outcome rather than cause of deficits in

these children's ability to maintain task-context information in short-term memory over an extended period of time. This hypothesis remains speculative, however, and experimental investigations are needed to disentangle the complex interrelationships among impaired storage/rehearsal processes and the tendency for children with ADHD to choose small, immediate rewards over larger, delayed rewards in situations that allow them to influence task duration. To date, only one study has investigated the relationship between delay aversion and short-term/working memory in children with ADHD. Karalunas and Huang-Pollock (2011) reported that children with ADHD were not more delay adverse than typically developing children, and that the relationship between delay aversion and short-term/working memory did not differ between children with and without ADHD. No study to date, however, has tested competing predictions from the working memory and delay aversion hypotheses to determine the extent to which any ADHD-related tendency toward a delay adverse motivational style remains after accounting for their well-established deficits in short-term and working memory.

The unique contribution of the current study was the dissociation of phonological storage and rehearsal components of working memory while controlling for reading speed, intelligence, age, SES, and input and output processes. Several caveats merit consideration despite these methodological refinements. The generalization of results 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. As an initial study, girls were excluded given evidence of subtle but significant neuropsychological differences in boys relative to girls with ADHD (Gaub and Carlson 1997), including fewer executive function impairments in girls relative to boys (Gunther et al. 2010; Seidman et al. 1997). Independent experimental replication with larger samples that include females, older children, and other ADHD subtypes is recommended to address these potential limitations. Our cell sizes, however, were sufficient based on an *a priori* power analysis. Smaller magnitude between-group differences might also be expected in studies including children with fewer or less disabling ADHD-related symptoms, as well as studies using fewer recall trials to assess phonological short-term capacity. Finally, several children with ADHD were comorbid for ODD; however, the degree of comorbidity may be viewed as typical of the ADHD population based on 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).

The ability to briefly store and maintain information represents a critical component of phonological working

memory. Deficiencies in these functions place significant constraints on the quantity of information that can be processed and manipulated over time, which is necessary for performing a wide range of tasks and activities that require the analysis of longer sequences of information (e.g., reading comprehension, multi-step instructions) and the reorganization and/or advanced processing of stored information (e.g., mental math computation).

As a result, remedial cognitive interventions and compensatory strategies that focus on improving phonological short-term storage capacity and/or implementing strategies that place fewer demands on this resource-limited mechanism may prove beneficial for children with ADHD. Nascent efforts aimed at increasing phonological storage capacity in children with ADHD are promising and associated with small (Holmes et al. 2009) to medium near-term effects (Klingberg et al. 2005) on untrained tasks. These interventions, however, target primarily short-term storage capacity, with only incidental training of the large magnitude rehearsal deficits identified in the current study. In future investigations, these types of cognitive training approaches may need to adopt active components that require children to hold information for progressively longer time intervals to promote development of the phonological short-term memory rehearsal mechanism. In-class educational compensatory strategies that reduce reliance on working memory may also hold promise; however, an initial investigation adopting this approach did not improve children's academic functioning significantly (Elliott et al. 2010). Finally, additional research is needed to identify whether phonological short-term memory deficits render children with ADHD more susceptible to interference effects (e.g., the susceptibility of previously learned information to interfere with the learning of new information). For example, combined fMRI/behavioral studies are needed to examine the extent to which group differences in rehearsal performance are attributable solely to the phonological rehearsal component, or whether some children utilize dual encoding or other strategies to attempt to improve delayed recall (e.g., visualizing to be recalled words). Documentation of increased susceptibility to interference may inform clinical practice regarding the need to include additional strategies to address this phenomenon.

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