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Phonological Working Memory Deficits in ADHD Revisited: The Role of Lower Level Information-Processing Deficits in Impaired Working Memory Performance

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Abstract

Objective: The current study dissociates lower level information-processing abilities (visual registration/encoding, visual-to-phonological conversion, and response output) and examines their contribution to ADHD-related phonological working memory (PHWM) deficits. **Method:** Twenty children with ADHD and 15 typically developing (TD) children completed tasks assessing PHWM, visual registration/encoding, visual-to-phonological conversion, and response output. **Results:** Relative to TD children, children with ADHD exhibited deficient visual registration/encoding (d = 0.60), visual-to-phonological conversion (d = 0.56), and PHWM (d = 0.72) but faster response output (d = –0.66). Bias-corrected, bootstrapped mediation analyses revealed that visual registration/encoding, but not visual-to-phonological conversion, partially mediated ADHD-related PHWM impairments. In contrast, faster response output in children with ADHD served as a suppressor variable, such that greater PHWM deficits were observed in children with ADHD after controlling for their faster response output (d = 0.72 vs. 0.85). **Conclusion:** Results implicate both lower level (visual registration/encoding) and higher order (PHWM) impairments in ADHD. Implications for designing educationally relevant cognitive interventions are discussed. *(J of Att. Dis. XXXX; XX(X) XX-XX)*

Keywords

ADHD, working memory, information processing, encoding, phonological conversion

The sequelae of ADHD often involve clinically significant and impairing educational decrements as evidenced by increased rates of learning disabilities (8%-76%; DuPaul, Gormley, & Laracy, 2013), academic achievement deficits (*d*s = 0.55 to 0.73; Frazier, Youngstrom, Glutting, & Watkins, 2007), and lower high school and college graduation rates (Barkley, Fischer, Smallish, & Fletcher, 2006). However, current gold-standard treatments for the disorder (i.e., psychostimulants, intensive behavioral treatments, or their combination) fail to normalize these education-related deficits (Döpfner et al., 2016; Molina et al., 2009; Van der Oord, Prins, Oosterlaan, & Emmelkamp, 2008). In recent years, working memory has emerged as a promising explanation for not only understanding a wide array of ADHD symptoms and functional impairments (Holmes et al., 2010; Kasper, Alderson, & Hudec, 2012; Martinussen, Hayden, Hogg-Johnson, & Tannock, 2005; Rapport, Alderson, et al., 2008) but also the development of novel treatments based on the underlying neurocognitive deficits identified (Melby-Lervåg, Redick, & Hulme, 2016; Rapport, Orban, Kofler, & Friedman, 2013).

Working memory is a limited capacity system responsible for the temporary storage, maintenance, processing, and manipulation of internally held information for use in guiding behavior. It has emerged as a particularly promising executive function for understanding a wide array of ADHD symptoms and functional impairments (Kasper et al., 2012; Rapport et al., 2008; Rapport et al., 2013). Extensive evidence reveals two anatomically distinct working memory subsystems—phonological and visuospatial —that are responsible for the temporary storage and maintenance of modality-specific information and whose functions are coordinated by a domain-general attentional controller termed the central executive (Baddeley, 2007). These functions are broadly correlated neuroanatomically with prefrontal/frontal neurocircuitry (e.g., Fassbender & Schweitzer, 2006) which have also been demonstrated to be hypoactive in children with ADHD (e.g., Dickstein, Bannon, Castellanos, & Milham, 2006). The central

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executive and its associated processes reflect the *working* components of working memory and are responsible for mentally processing internally held information (Wager & Smith, 2003).

Phonological working memory (PHWM) refers to the domain-general central executive operating in tandem with the phonological short-term memory system, and warrants particular scrutiny for several reasons. These include the (a) moderate to large magnitude PHWM deficits evidenced by children with ADHD (Bolden, Rapport, Raiker, Sarver, & Kofler, 2012; Martinussen & Tannock, 2006; Rapport, Alderson, et al., 2008); (b) PHWM subsystem's involvement in a wide range of academic abilities (Cain, Oakhill, & Bryant, 2004; L. Swanson & Kim, 2007); and (c) large overlap between ADHD and learning-related difficulties (DuPaul et al., 2013).

Recent evidence (Karalunas & Huang-Pollock, 2013) suggests, however, that PHWM deficits in children with ADHD may be explained partially by deficits in lower level cognitive processes involved in converting visual stimuli to phonological code (i.e., visual registration/encoding, visual-to-phonological conversion, response output; Figure 1). Examination of lower level processes is a requisite and critically important precursor to understanding ADHD-related PHWM deficits, given their ubiquity in academic tasks in school settings (Figure 1). For example, when completing an applied math problem, visual elements (e.g., graphs, picture problems) must be visually encoded initially and subsequently converted into language (phonological code). The degree to which these lower level component processes are affected has important implications for understanding PHWM deficits and their impact across areas of academic performance. For example, slowed registration and encoding would delay the rate at which visual information converts into phonological code and limits efficient PHWM processing. The phonological system's intricate involvement across broad areas of academic functioning (Cain et al., 2004; Montgomery, 1995; H. L. Swanson & Howell, 2001) underscores the importance of fractionating the PHWM system's underlying, lower level cognitive subprocesses to better understand the nature of these deficits in children with ADHD. In addition, the failure of existing cognitive training programs to produce far-transfer improvements in academic functioning has been demonstrated repeatedly (Chacko et al., 2013; Rapport et al., 2013; Shipstead, Redick, & Engle, 2012) and highlights the need to investigate more nuanced treatment targets (e.g., lower level cognitive subprocesses) in hopes of improving these outcomes for children with ADHD.

To date, only three studies have examined the association between deficits in information processing and working memory in children with ADHD, with two studies suggesting that lower level information processing partially explains higher order PHWM deficits (Jacobson et al., 2011; Karalunas & Huang-Pollock, 2013), and one study showing a nonsignificant relation (Alderson et al., 2015). Importantly, no study to date has disassociated all three information-processing subcomponents (visual registration/encoding, visual-to-phonological conversion, response preparation/output; Figure 2) to determine their unique contribution to ADHD-related PHWM deficits.

The current study is the first to fractionate these lower level information-processing subcomponents, and examine the extent to which each subcomponent is impaired and adversely affects higher order PHWM in children with ADHD relative to typically developing (TD) children. Understanding the relative contribution of these processes and the extent to which they contribute to ADHD-related PHWM deficits has potentially important implications for the design of efficacious remedial and/or preventive interventions to improve their academic functioning. Consistent with previous studies, we hypothesized that children with ADHD would demonstrate impaired visual registration/encoding (Ballesteros, Reales, & García, 2007) and/or visual-to-phonological conversion (Banaschewski et al., 2006; Lawrence et al., 2004; Rucklidge & Tannock, 2002; Shanahan et al., 2006; Tannock, Martinussen, & Frijters, 2000; Wodka et al., 2008),[1] but faster response output (Kofler et al., 2013). We also hypothesized that visual encoding and/or phonological conversion processes would partially mediate the magnitude of ADHD-related PHWM deficits (Jacobson et al., 2011; Karalunas et al., 2013). Conversely, we expected response output to function as a suppressor variable given the expectation that children with ADHD would exhibit faster response output relative to TD children (Kofler et al., 2013).

Method

Participants

The sample comprised 35 native English speaking boys aged 8 to 12 years, referred to a children's learning clinic through community resources (e.g., referrals from pediatricians, self-referral). The exclusive inclusion of boys reflects evidence suggesting sex differences in the prevalence and course of ADHD symptoms, as well as the magnitude and nature of ADHD-related neurocognitive impairments (Bálint et al., 2009; Williamson & Johnston, 2015). Sample race and ethnicity included 24 Caucasian Non-Hispanic, seven Hispanic, and four biracial children. No between-group differences in the distribution of race and ethnicity in children with ADHD relative to TD children emerged (χ^2, p = .45; Table 1). All parents and children provided their informed consent/assent, and approval from the university's institutional review board (IRB) was obtained prior to data collection. Children with ADHD and TD children without a psychological disorder participated in this study. Children with a history of (a) gross neurological, sensory, or motor impairment by parent report, (b) history of a seizure disorder by parent report, (c) psychosis, or (d) Full Scale IQ score $\leq$ 85 were excluded.

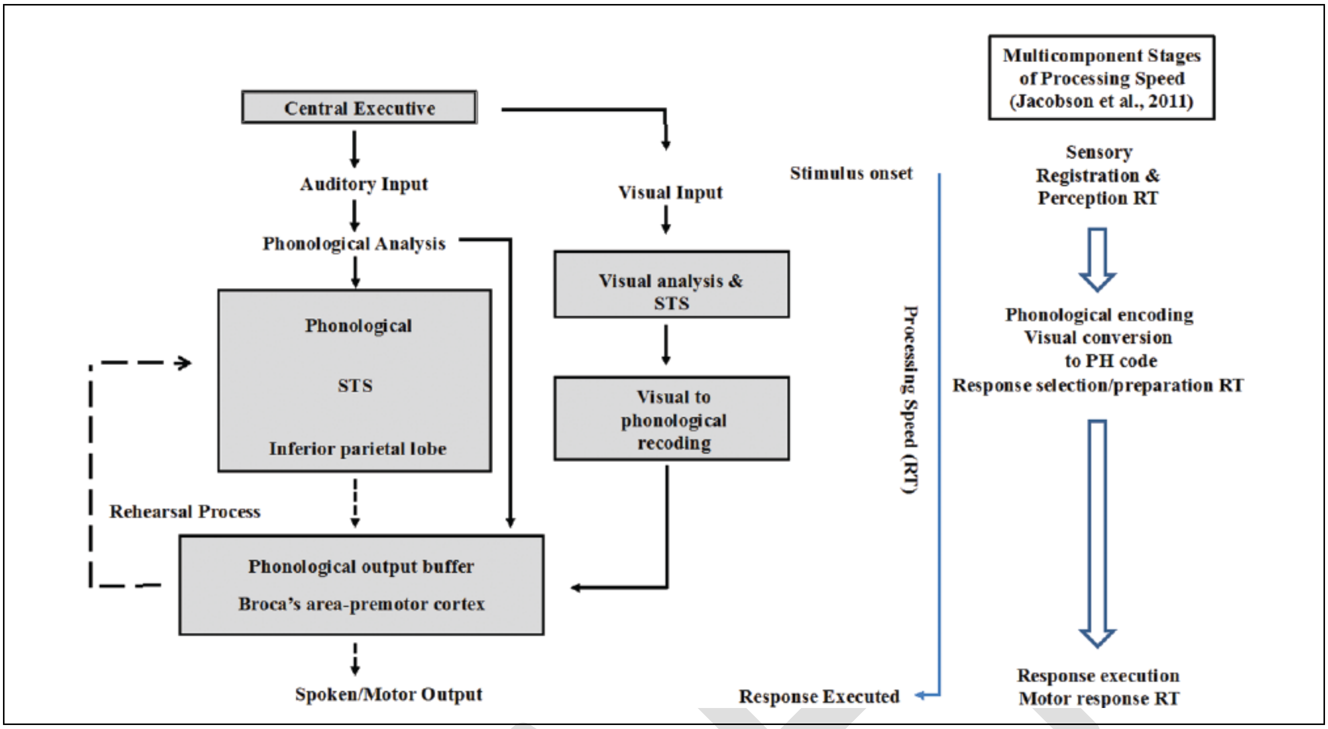

Figure 1. Adapted and expanded version (with permission from author) of Baddeley's (2007) phonological working memory subsystem and corresponding components of information-processing speed from stimulus onset to response output based on Jacobson et al. (2011).
Note. STS = short-term store; RT = reaction time; PH = phonological; LTM = long-term memory.

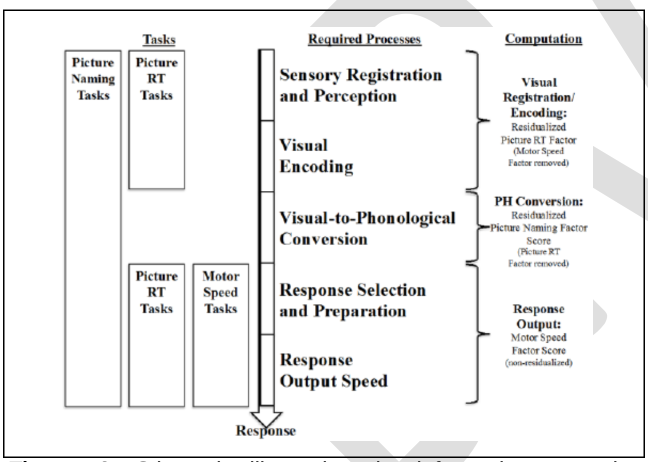

Figure 2. Schematic illustrating the information-processing subcomponents examined in the current study (middle column), the experimental tasks used to derive indices of each information-processing subcomponent (left), and the statistical method for deriving reliable variance associated with each subcomponent (right).
Note. RT = reaction time; PH = phonological.

Group Assignment

All children and their parents were administered a semistructured interview (i.e., Kiddie Schedule for Affective Disorders and Schizophrenia for School-Aged Children [K-SADS]) to assess current and past episodes of psychopathology based on *Diagnostic and Statistical Manual of Mental Disorders* (4th ed.; *DSM-IV*; American Psychiatric Association, 1994) criteria. The psychometric properties of the K-SADS are well established (Kaufman et al., 1997).

Twenty children meeting the following criteria were included in the ADHD-Combined Type group: (a) an independent diagnosis by the clinic's directing psychologist using *DSM-IV* criteria for ADHD-Combined Type based on parent and child K-SADS interview[2]; (b) parent ratings of at least 2 *SD*s above the mean on the ADHD Problems *DSM*-Oriented scale of the Child Behavior Checklist (CBCL; Achenbach & Rescorla, 2001), or exceeding the criterion score for the parent version of the ADHD-Combined subtype subscale of the Child Symptom Inventory–4: Parent Checklist (CSI-P; Gadow, Sprafkin, & Salisbury, 2004); and (c) teacher ratings of at least 2 *SD*s above the mean on the ADHD Problems *DSM*-Oriented scale of the Teacher Report Form (TRF; Achenbach & Rescorla, 2001), or exceeding the criterion score for the teacher version of the ADHD-Combined subtype subscale of the Child Symptom Inventory–4: Teacher Checklist (CSI-T; Gadow et al., 2004). The psychometric properties of the CBCL, TRF, and CSI are well established (Rapport, Kofler, Alderson, & Raiker, 2008). Eleven of the ADHD children were on a

Table 1. Sample and Demographic Variables.

Variable	ADHD *M*	ADHD *SD*	Typically developing *M*	Typically developing *SD*	*F*
Age	9.60	1.08	9.97	1.38	0.81
FSIQ	104.65	8.92	109.67	11.54	2.11
SES	53.43	7.68	53.23	11.32	0.004
CBCL					
AD/HD problems	71.10	8.40	53.27	6.94	44.61***
TRF					
AD/HD problems	66.65	7.36	53.00	5.35	36.89***
CSI-Parent					
ADHD, Combined	77.35	10.16	46.80	11.26	70.68***
CSI-Teacher					
ADHD, combined	68.10	9.01	45.40	5.68	73.12***
Dependent variables	Cohen's *d*				
Response output factor score	–0.66*				
Visual encoding factor score	0.60*				
Phonological conversion factor score	0.56*				
Phonological working memory factor score	–0.72*				

Note. Response output speed was reverse scored such that lower scores indicate better (i.e., faster) performance to maintain consistency across information-processing speed metrics. FSIQ = Full Scale Intelligence Quotient; SES = socioeconomic status; CBCL = Child Behavior Checklist; TRF = Teacher Report Form; CSI = Child Symptom Inventory severity *T*-scores.
*90% confidence interval does not include 0.0. ***$p \leq .001$.

psychostimulant regimen (24-hr washout period prior to each session). Nine of the 20 children with ADHD also met criteria for Oppositional-Defiant Disorder based on ratings exceeding the criterion score on the parent or teacher CSI. Two of the children with ADHD were comorbid for additional *DSM-IV* childhood psychological disorders unrelated to study hypotheses (i.e., specific phobia, anxiety disorder).

Fifteen children met the following criteria and were included in the TD group: (a) no evidence of any clinical disorder based on parent and child K-SADS interview, (b) normal developmental history by parental report, (c) ratings within 1.5 SDs of the mean on all CBCL and TRF scales, and (d) parent and teacher ratings within the nonclinical range on all CSI subscales.[3]

Procedures

All working memory and information-processing tasks were administered in English as part of a larger battery requiring the child's presence for approximately 3 hr per session across four consecutive assessment sessions. Performance was monitored at all times by an examiner, who was stationed just outside the child's view. All children received brief (2-3 min) breaks following each task, and longer (10-15 min) breaks after two to three tasks to minimize fatigue.

Due to experimenter error, three children received the same stimuli order for both administrations of Picture Naming ($n = 2$) or Picture Reaction Time (RT; $n = 1$). No significant differences were detected between these children and the children receiving parallel forms of stimuli presentation order (all p values ≥ .20). In addition, two children completed the Picture Naming ($n = 1$) or Picture RT ($n = 1$) task only once resulting in approximately 0.6% missing data. Group mean substitution was used for children with missing data to allow computation of factor scores.

Measures

PHWM tasks. The PHWM tasks used in this study are identical to those described by Rapport, Alderson, and colleagues (2008).[4] Each child was administered four PHWM conditions (set sizes 3, 4, 5, and 6). The four PHWM set size conditions (lasting 2-6 min) each contained 24 unique trials (lasting 3-6 s per trial) of the same set size, and were counterbalanced across the four testing sessions to control for order effects and potential proactive interference effects across set size conditions. The working memory tasks have high internal consistency (α = .75-.90) in the current sample and the expected level of external validity (r = .50-.66) with Wechsler Intelligence Scale for Children (WISC) Digit Span raw scores (Raiker, Rapport, Kofler, & Sarver, 2012).

The PHWM tasks are similar to the Letter-Number Sequencing subtest on the Wechsler Intelligence Scale for Children–Fourth Edition (WISC-IV; Wechsler, 2003). Children were presented a series of jumbled numbers and a capital letter on a computer monitor. Stimuli appeared sequentially for 800 ms each (200 ms interstimulus interval [ISI]) and children had up to 30 s to respond orally prior to the presentation of the next series of stimuli. The letter never appeared in the first or last position to minimize potential primacy and recency effects. Trials were counterbalanced such that letters appeared an equal number of times in the other serial positions. 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 should have been correctly recalled as 2 4 6 H in the set size 4 condition). Children completed five practice trials prior to each administration (≥80% correct required). If children did not meet the 80% minimal accuracy criteria during the practice trials, they were readministered the practice trials until 80% accuracy was demonstrated. All children met the 80% minimal criteria before proceeding with the tasks. Two trained research assistants recorded oral responses independently. Interrater reliability ranged from .97 to 1.0.

Information-processing tasks: The tasks described below were administered in counterbalanced order across the four sessions such that each child received each task on two occasions, 1 week apart. The tasks were designed such that each task required a specific combination of the information-processing subcomponents (Figure 2), allowing a regression-based, factor approach to statistically isolate reliable variance associated with each information-processing stage. Scores for the two administrations of each task were combined using principal components factor analysis. A one-factor solution was preferred for all constructs based on first factor eigenvalue > 1.0 and second factor eigenvalue < 1.0. The N-to-K ratio of 35:2 was considered adequate for deriving each information-processing component (Hogerty, Hines, Kromrey, Ferron, & Mumford, 2005).

Picture Naming Task. The Picture Naming Task required children to (a) visually register and encode pictures (visual registration/encoding), (b) convert these visual stimuli to phonological code (visual-to-phonological conversion), and (c) verbally indicate the object's name while pressing a response key as quickly as possible (response output). Verbal responses were required to ensure visual-to-phonological conversion; five practice trials were administered with coaching and repeated until children successfully responded to all five trials. Thirty monochrome, familiar stimuli were selected from an open source clipart repository (http://www.graphicsfactory.com) based on the criteria that they were clearly drawn and easily recognizable archetypes, and had monosyllabic names (e.g., car). Thirty additional unfamiliar monochrome stimuli were included and consisted of unique Chinese characters, to which children were required to respond "no." These were added as catch trials to decrease the likelihood of anticipatory responding, as part of a larger study examining serial/parallel long-term memory search termination processes, and are not included in the calculation of the primary indices described below. None of the children understood the meaning of the Chinese characters.

The task was approximately 2 to 3 min in length and displayed 60 stimuli (30 familiar, 30 unfamiliar) in random order at an average rate of one stimulus/second (jittered randomly between 800, 1000, and 1200 ms to decrease anticipatory responding). Anticipatory responses (trial RT < 150 ms) were excluded. Mean reaction time (MRT) for correct responses across the 30 familiar stimuli served as the primary outcome variable. There were no significant between-group differences in the number of correct trials greater than 150 ms across both tasks (ADHD mean ranged from 28.90 to 29.42, TD mean ranged from 29.40 to 29.80; both $p \geq .18$). A Picture Naming factor score was computed for all children via principal components factor analysis (both factor loadings = 0.94; eigenvalue = 1.77) and reflects reliable variance associated with all of the information-processing subcomponents (Figure 2).

Picture RT task. The Picture RT task was identical to the Picture Naming Task described above in every aspect except for the visual-to-phonological conversion demands. The Picture RT task was approximately 2 to 3 min in length and required children to (a) visually register/encode and (b) prepare and provide a skeletomotor response to each visually presented stimuli (Figure 2). The same 60 stimuli described in the Picture Naming tasks were used to equate these counterbalanced tasks as closely as possible. Children were instructed to press a response key as quickly as possible each time any picture appeared, regardless of its content. Five practice trials were administered until children responded successfully to all five trials; children whose counterbalancing resulted in them completing the Picture Naming tasks in prior sessions were instructed explicitly not to name the stimuli. Examination of raw task performance indicated that the experimental manipulation (addition of visual-to-phonological conversion demands for Picture Naming vs. Picture RT) was successful based on significantly longer mean RTs during the Picture Naming (MRT = 971.71 ms, SD = 264.77 ms) relative to Picture RT tasks (MRT = 436.58 ms, SD = 89.56 ms; $p < .0001$).

MRT for correct responses across the 30 familiar stimuli served as the primary outcome variable to equate performance across the Picture Naming and Picture RT tasks. There were no significant between-group differences in the number of correct trials greater than 150 ms used across both tasks (ADHD mean ranged from 29.16 to 29.35, TD mean ranged from 29.73 to 29.93; both $p \geq .07$). A Picture RT score was computed for all children via principal components factor analysis (both factor loadings = 0.83; eigenvalue = 1.37) and reflects reliable variance associated with the visual registration/encoding and response output subcomponents of the information-processing model (Figure 2).

Motor speed task. The motor speed task was approximately 10 s in length and used to assess response output speed. Children were instructed to press a response key using their index finger as quickly and as many times as possible for 10 s. The task indexes children's basic response output independent of the additional processes associated with encoding, processing, and responding to a stimulus; the short duration was selected to minimize fine motor muscle fatigue. A practice trial was administered prior to each administration. The number of correct presses per second served as the dependent variable. Key presses on buttons other than the designated response key were excluded. A Motor Speed factor score was computed for each child via principal components factor analysis (both factor loadings = 0.77; eigenvalue = 1.20) and reflects reliable variance associated with the response output subcomponents of information-processing model (Figure 2).

Measured intelligence. Full Scale IQ (FSIQ; Wechsler, 2003) was obtained from the WISC-IV.

Dependent Variables

PHWM. A factor score reflecting overall PHWM performance was created using stimuli correct per trial at each set size to extract shared variance across all four set size conditions (all factor loadings ≥ 0.79; eigenvalue = 2.64) as recommended (cf. Conway et al., 2005). The N-to-K ratio of 35:4 was considered adequate for deriving the factor scores (Hogerty et al., 2005).

Visual registration/encoding. Visual registration/encoding was estimated by residualizing the Motor Speed factor score from the Picture RT factor score (R^2 = .002). Residual variance in Picture RT reflects visual registration/encoding after removing performance associated with response output. As indicated by the small R^2, performance on the Picture RT task was influenced minimally by response output. Thus, residualizing the Picture RT task provided minimal incremental improvement in our estimates, and the overall pattern of results remained largely unchanged when using the unresidualized versus residualized factor scores. Results reflect residualized factor scores.

Visual-to-phonological conversion. Visual-to-phonological conversion was estimated by residualizing the Picture RT factor score from the Picture Naming factor score (R^2 = .02). Residual variance in Picture Naming reflects visual-to-phonological conversion after removing performance associated with visual registration/encoding and response output.

Response output. The Motor Speed factor score described above served as the primary index of response preparation and skeletomotor speed. To facilitate interpretation, Motor Speed was reverse scored so that higher values reflect slower performance for all information-processing metrics.

Mediation Analysis

Analyses were completed using a bias-corrected bootstrapping procedure to minimize Type II error. In addition, bootstrapping was used to evaluate the intercorrelations among all of the variables as well as to determine the statistical significance of all total, direct, and indirect effects (Figure 3a). All continuous variables were standardized as *z* scores based on the full sample to facilitate between- and within-model comparisons and allow unstandardized regression coefficients (*B* weights) to be interpreted as Cohen's *d* effect sizes when predicting from a dichotomous grouping variable (Hayes, 2009). The PROCESS script for SPSS (Hayes, 2013) was used for all analyses, and 10,000 samples were derived from the original sample (N = 35) by a process of resampling with replacement (Shrout & Bolger, 2002).

Effect ratios (indirect effect divided by total effect) estimated the proportion of each significant total effect that was attributable to the indirect effect. Ninety percent confidence intervals were selected over 95% confidence intervals because the former are more conservative for evaluating mediating effects (Shrout & Bolger, 2002).[5] A two-tiered data analytic approach was adopted for the study. Intercorrelations among the primary dependent variables were examined in Tier I. Significantly correlated dependent variables were retained in the Tier II analyses to examine the mediating impact of the information-processing subcomponents on ADHD-related PHWM deficits.

Results

Power Analysis

A large magnitude effect size (ES) was predicted based on established large magnitude relations between ADHD and PHWM (ES = 2.01; Kasper et al., 2012), between ADHD and processing speed (ES = 0.61 to 0.93; Kofler et al., 2013), and between working memory and processing speed (r = .68; Schmiedek, Oberauer, Wilhem, Süβ, & Wittman, 2007). Mediation analysis using the bias-corrected bootstrapping procedure requires 34 total participants to achieve .80 power (Fritz & MacKinnon, 2007). Thirty-five children were included in the current study.

Preliminary Analysis

No univariate (scores exceeding 3.5 *SD*s) or multivariate outliers (significant Mahalanobis distance tests [$p < .001$]) were identified. As expected, scores on the rating scales were significantly higher for the ADHD group relative to the TD group (Table 1); however, children with ADHD did not differ in age (p = .38), FSIQ (p = .16), or socioeconomic status (SES; p = .95). As a result, simple model results with no covariates are reported.

Tier I: Intercorrelations

Positive relations between ADHD status and information processing indicate that children with ADHD (0 = TD, 1= ADHD) performed significantly slower on the information-processing tasks. In contrast, negative relations between ADHD status and PHWM indicate worse working memory performance in the ADHD group. ADHD status was related significantly to impaired PHWM performance (r = –.36; 90% CI = [–0.58, –0.13]), slower visual registration/encoding (r = .31; 90% CI = [0.02, 0.56]), and slower conversion of visual stimuli to phonological code (r = .29; 90% CI = [0.01, 0.53]). In

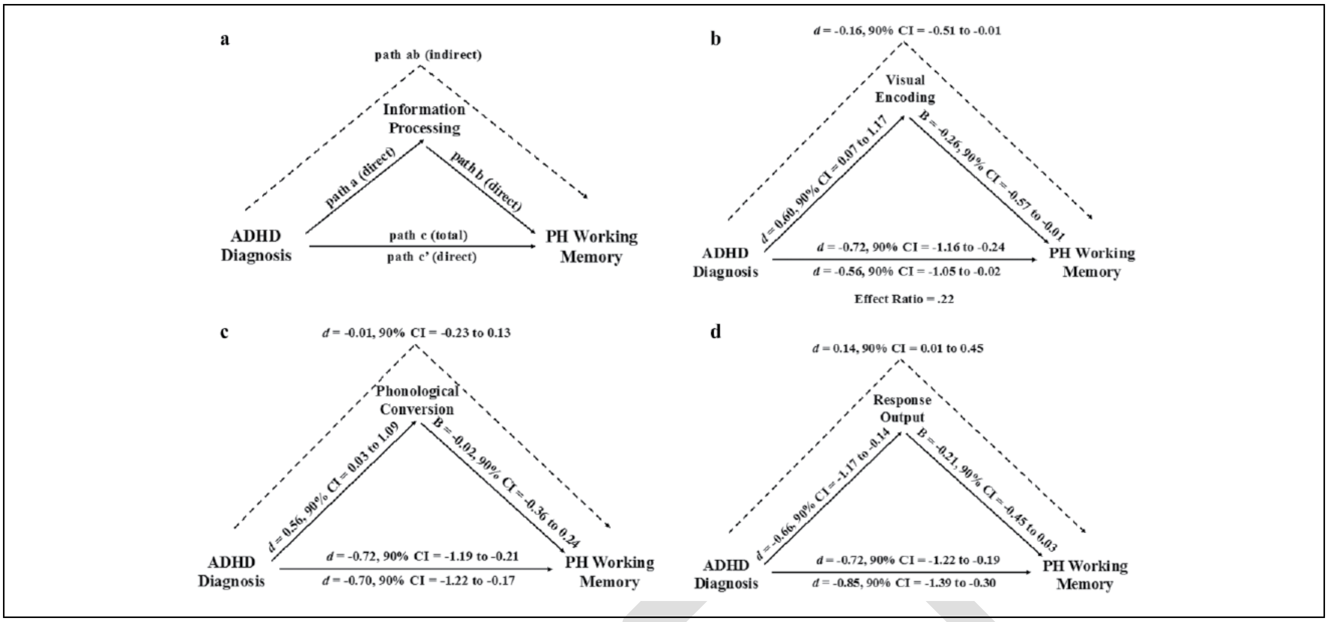

Figure 3. Schematics depicting (a) the effect sizes and *B* coefficients of the total, direct, and indirect pathways for the mediating effect of (b) visual registration/encoding, (c) visual conversion, and (d) response output speed on phonological working memory.
Note. The change in confidence interval for the c pathway across analyses is a result of the production of a new distribution of estimates of the total effect with each new bootstrapped mediation analysis. Cohen's *d* for the c and c′ pathways reflects the imapct of ADHD diagnostic status on phonological working memory performance before (path c) and after (path c′) taking into account the mediating variables.

contrast, ADHD status was associated with faster response output (r = –.33; 90% CI = [–0.55, –0.10]). Slower visual registration/encoding was associated with greater deficits in PHWM (r = –.34; 90% CI = [–0.53, –0.16]), whereas response output speed (r = –.06; 90% CI = [–.30, 20]) and visual conversion (r = –.12, 90% CI = [–0.37, 0.13]) were not related significantly to PHWM performance**”**. Based on this pattern of results, all three information-processing subcomponents were retained for the Tier II mediation analyses (i.e., a statistically significant relation is required for one but not both pathways to justify mediation analyses; Hayes, 2009).

Tier II: Mediation Analyses

Total effect. Examination of the total effect (Figure 3, path c; Table 2) revealed that ADHD status was related significantly to PHWM (Cohen's d = –0.72), such that children with ADHD demonstrated large magnitude PHWM deficits prior to accounting for the potential mediating role of lower level information-processing components.

Visual registration/encoding mediating ADHD PHWM deficits. ADHD status was associated significantly with slower registration/encoding of visual stimuli (Cohen's d = 0.60; Figure 3b, path a; Table 2). Slower visual registration/encoding was also related to worse PHWM performance (β = –0.26; Figure 3b, path b) after controlling for ADHD status. Examination of the mediation pathway (Figure 3b, path ab) revealed that ADHD status exerted a significant, small magnitude indirect effect on PHWM (Cohen's d = –0.16; 90% CI = [–0.51, –0.01]) through its impact on lower level visual registration/encoding processes. Specifically, visual registration/encoding accounted for approximately one fifth of the relation between ADHD status and PHWM (Effect Ratio = .22), and thus was associated with a moderate reduction in the magnitude of ADHD-related PHWM deficits (d changed from –0.72 to –0.56). The direct relation between ADHD status and PHWM remained significant after accounting for visual registration/encoding deficits (d = –0.56, 90% CI = [–1.05, –0.02]).

Phonological conversion mediating ADHD PHWM deficits. ADHD status was associated significantly with slower visual-to-phonological conversion (Cohen's d = 0.56; Figure 3c, path a; Table 2). Phonological conversion was not associated with PHWM (β = –0.02; Figure 3c, path b) after controlling for ADHD status. The confidence interval for the mediation pathway included zero and was nonsignificant (Figure 3c, path ab), indicating that PHWM deficits in children with ADHD cannot be explained by their impairments in phonological conversion (indirect effect: Cohen's d = –0.01; 90% CI = [–0.23, 0.13]). The direct relation between ADHD status and PHWM remained significant (d = –0.70, 90% CI = [–1.22, –0.17]) after accounting for phonological conversion deficits.

Table 2. Mediation Analysis: Impact of Diagnostic Status (TD, ADHD) and Information Processing on Phonological Working Memory.

		Information processing					
		Visual registration/encoding		Phonological conversion		Response output	
Path		*d*[a]	(*SE*)	*d*[a]	(*SE*)	*d*[a]	(*SE*)
	Total effect						
c	Diagnosis → PH Working Memory	−0.72[b]	(0.31)	−0.72[b]	(0.31)	−0.72[b]	(0.31)
	90% CI	[−1.16, −0.24]		[−1.19, −0.21]		[−1.22, −0.19]	
	Direct effects						
a	Diagnosis → Information Processing	0.60[b]	(0.32)	0.56[b]	(0.33)	−0.66[b]	(0.31)
	90% CI	[0.07, 1.17]		[0.03, 1.09]		[−1.17, −0.14]	
b	Information Processing → PH Working Memory	−0.26[b]	(0.17)	−0.02	(0.18)	−0.21	(0.15)
	90% CI	[−0.57, −0.01]		[−0.36, 0.24]		[−0.45, 0.03]	
c′	Diagnosis → PH Working Memory	−0.56[b]	(0.35)	−0.70[b]	(0.35)	−0.85[b]	(0.34)
	90% CI	[−1.05, −0.02]		[−1.22, −0.17]		[−1.39, −0.30]	
	Indirect effects (through mediator)						
ab	Diagnosis → PH Working Memory						
	Bootstrap Estimate	−0.16[b]	(0.14)	−0.01	(0.11)	0.14[b]	(0.13)
	90% CI of bootstrap	[−0.51, −0.01]		[−0.23, 0.13]		[0.01, 0.45]	
	Effect ratio	0.22		—		—	

Note. Paths labels reflect standard nomenclature (cf. Fritz & MacKinnon, 2007) and are depicted in Figure 3; c and c′ reflect the total and direct effect of Diagnosis on PH working memory before and after accounting for visual registration/encoding. The change in confidence interval for the c pathway across analyses is a result of the production of a new distribution of estimates of the total effect with each new bootstrapped mediation analysis. Lower scores on the visual registration/encoding factor indicate better (i.e., faster) performance. TD = typically developing; PH = phonological; CI = confidence interval.

[a]Values in the *d* column for path b reflect *B* weights due to the use of two continuous variables in the calculation of the direct effect.

[b]Effect size (or *B* weight) is significant based on 90% confidence intervals that do not include 0.0 (Shrout & Bolger, 2002).

Response output mediating ADHD PHWM deficits. ADHD status was associated with significantly faster response output (Cohen's d = –0.66; Figure 3d, path a; Table 2); however, response output speed was not associated with PHWM performance (β = –0.21; Figure 3d, path b) after controlling for ADHD status. Examination of the mediation pathway (Figure 3d, path ab) revealed that the presence of faster response output speed in children with ADHD resulted in the suppression of between-group differences in PHWM as evidenced by a significant, small magnitude indirect effect on PHWM (Cohen's d = 0.14; 90% CI = [0.01, 0.45]) in the opposite direction of the direct effect of diagnostic status on PHWM (Shrout & Bolger, 2002). Specifically, the magnitude of ADHD-related PHWM deficits increased somewhat after controlling for the faster response output speed exhibited by children with ADHD (d changed from –0.72 to –0.85).

Discussion

The well-documented working memory deficits associated with ADHD (Kasper et al., 2012), combined with the inefficacy of cognitive training programs (Rapport et al., 2013) and medication (Rubia et al., 2013) for targeting brain regions associated with working memory, provide a compelling impetus for research examining the interrelations among subcomponents of these systems. This study is the first to fractionate and examine the contribution of three subcomponents of lower level information processing to PHWM performance for children with and without ADHD.

Consistent with past research, the current study revealed moderate magnitude PHWM deficits in children with ADHD (Cohen's d = –0.72). In contrast, children with ADHD exhibited faster response output speed (Cohen's d = –0.66) relative to their TD peers, which exerted a suppressor effect on PHWM deficits in children with ADHD. That is, statistically controlling for the faster response output speeds exhibited by children with ADHD revealed larger magnitude PHWM impairments than were detected prior to mediation analysis (Δd from –0.72 to –0.85). These findings appear at odds with those of a recent study in which response selection, but not motor speed deficiencies, predicted PHWM performance (Jacobson et al., 2011). It is important to note, however, that the tasks used by Jacobsen and colleagues provided a single score taken at the conclusion of a task, whereas computerized skeletomotor tasks such as those used in the current study record response time following each stimulus. In addition, the findings of the current study are consistent with recent meta-analytic findings of more variable but *faster* motor speed in children with ADHD (Kofler et al., 2013).

In contrast to their faster motor speed, children with ADHD demonstrated significant and similar magnitude impairments in visual registration/encoding (Cohen's d = 0.60) and visual-to-phonological conversion (Cohen's d = 0.56) consistent with past reports of overall slower completion rates for children with ADHD on tasks that require a combination of these and other lower level processes (e.g., Banaschewski et al., 2006), and provide initial evidence implicating visual encoding and phonological conversion, but not response output, in ADHD-related slowed information processing. These findings are inconsistent, however, with a previous investigation that reported no significant visual-to-phonological encoding deficits in children with ADHD (Alderson et al., 2015), likely reflecting methodological differences between the two studies (e.g., the current study's use of familiar objects rather than overlearned letters and numbers). In addition, the current findings are consistent with an emerging literature (e.g., Huang-Pollock, Karalunas, Tam, & Moore, 2012; Karalunas, Geurts, Konrad, Bender, & Nigg, 2014) reporting that children with ADHD mentally accumulate information less quickly and efficiently than their peers based on sophisticated diffusion modeling that disassociates mental processes involved in two-choice RT tasks (i.e., slower drift rate and nondecision time components). Notably, our use of simple, single-choice RT tasks (relative to the two-choice RT tasks required for diffusion modeling), suggests that information-processing deficiencies may occur at an even lower level than previously hypothesized.

Examining the extent to which these lower level processes were associated with higher order PHWM deficits, however, was of greater interest. Interestingly, mediation analyses revealed that children's visual registration/encoding speed, but not their ability to rapidly convert visual information to phonological code, significantly mediated the relation between ADHD diagnostic status and PHWM performance and accounted for approximately one fifth of ADHD children's PHWM deficits (Δd from –0.72 to –0.56). These findings highlight the role of both lower level (visual registration/encoding) and higher order (working memory) processes in these children's well-documented poor PHWM performance and extend previous work suggesting a mediating role for information-processing speed on the relation between working memory and teacher-rated classroom behavior for children with ADHD (Jarrold, Mackett, & Hall, 2014). The most parsimonious explanation for these findings appears to be that children with ADHD take longer to register and encode visual information, which restricts the rate at which information becomes available for processing and rehearsal within PHWM. In other words, slowed progression of visual information through the early stages of information-processing appears to create a bottleneck that limits the rate at which the phonological system gains access to this information. Inefficient entry into the short-term store, in turn, places clear limits on higher order information processing within PHWM and is associated with impaired learning across a wide range of academic activities (Gathercole, Alloway, Willis, & Adams, 2006). This finding is inconsistent with findings of Karalunas and colleagues (2013) using sophisticated diffusion modeling which found that speed of information uptake accounted for approximately 20% of ADHD PHWM deficits. Despite its novel approach, the study was not designed to dissociate the independent contribution of visual encoding and response output processes critical for successful information processing. Combining across these processes may have obfuscated detection of their role in explaining ADHD-related PHWM deficits given past (Ballesteros et al., 2007; Kofler et al., 2013) and current findings of *faster* response output but *slower* visual encoding in children with ADHD.

It seemed likely that ADHD-related PHWM deficits would be further explained by their inefficient conversion of visual information into phonological code; however, the nonsignificant mediation effect for this construct, despite medium magnitude between-group differences (d = 0.56), was inconsistent with this view and suggests that their slowed visual-to-phonological conversion abilities exert minimal impact on their PHWM deficits. One potential explanation for this discrepancy may be that the magnitude of their phonological conversion impairment was insufficient to result in problems given the stimulus presentation rate on the PHWM task. Examination of the raw data suggests that children with ADHD take, on average, 120 ms longer than TD children to convert a visually presented stimulus to phonological code.[6] Thus, their slowed visual-to-phonological conversion abilities may not have interfered with performance on working memory tasks that presented each stimuli for 800 ms (200 ms ISI)—that is, the working memory tasks' parameters may have allowed sufficient time to compensate for their overall slowed visual-to-phonological conversion abilities. Future research using varied presentation durations and/or stimuli with greater complexity is needed to evaluate this hypothesis.

Despite methodological (e.g., multiple administrations of each task and dissociation of multiple information-processing components) and statistical (e.g., bootstrapped mediation) refinements, limitations are inherent to all research investigations. Future studies are likely to benefit from larger and more diverse samples that include females, younger children and adolescents, and children comorbid for processing disorders. Furthermore, given the moderate sample size, efforts were made to increase internal reliability of the study (e.g., multiple administrations of each task across weeks, multitask measurements, and statistical control for various types of errors). The use of multiple administrations of each task lengthened the overall testing battery which may have resulted in fatigue effects (despite frequent breaks) in some children (e.g., children with ADHD); however, the counterbalanced nature of the assessment battery across participants is likely to have attenuated some of these potential fatigue effects. Studies incorporating briefer assessments to minimize the length of task administration are warranted to evaluate the extent to which extended assessment batteries impact performance and are likely to have important clinical implications for practitioners. Despite adequate power for detecting effects of the expected magnitude (Fritz & MacKinnon, 2007), we acknowledge that generalization to the broader population requires replication with larger samples. Finally, our decision to use MRT rather than RT variability as indices of the information-processing subcomponents was based on recent empirical evidence and theoretical accounts of these processes. For example, recent investigations found that RT variability is better characterized as an outcome rather than a cause of deficient working memory processes (Kofler et al., 2014; Shahar, Teodorescu, Usher, Pereg, & Nachshon, 2014). In addition, the experimental manipulations were hypothesized specifically to impact mean response times due to the systematic addition of time-consuming task requirements (e.g., phonological conversion), whereas converging evidence suggests that task demands minimally affect response variability (Kofler et al., 2013). Accounts of the interrelation between information processing and PHWM predict that overall speed of visual registration/encoding and conversion, not the variability of this basic information processing, influence PHWM (Fry & Hale, 2000).

The distinctiveness of the lower level information-processing stages and their unique associations with PHWM performance are consistent with their unique neuroanatomical circuitry. For example, visual registration is localized primarily to the superior parietal and supplementary motor area regions (e.g., Houdé, Rossi, Lubin, & Joliot, 2010; Tan, Laird, Li, & Fox, 2005), both of which are implicated in verbal working memory (Jonides et al., 1998). In contrast, tasks involving orthographic to phonological conversion correspond with inferior parietal and temporal regions (Houdé et al., 2010; Tan et al., 2005). Furthermore, both processes recruit left inferior frontal areas (Booth et al., 2004), whereas concurrent use of these processes in tandem is associated with additional activation in the visual word form area of the fusiform cortex (Tan et al., 2005).

The impact of visual registration/encoding on ADHD children's PHWM deficits has important implications for interventions aimed at improving behavioral symptoms and functional outcomes associated with the disorder. The failure of current cognitive interventions to attenuate impairments in ADHD (cf. Rapport et al., 2013) may be due to their narrow focus on improving the less impaired aspects of working memory functioning (i.e., short-term storage) as indicated by Chacko and colleagues (2013) as well as a lack of focus on remediating more basic cognitive processes (e.g., visual registration/encoding) necessary for optimal working memory functioning. Given recent demonstrations that improvements in information-processing speed are achievable through training (Mackey, Hill, Stone, & Bunge, 2011), future interventions may benefit from the inclusion of components that vary the speed with which visual information must be processed. Adaptive training methodology is well suited for this purpose because it allows ongoing adjustments in presentation rate to be made based on children's performance.

This study implicates both lower level and higher order neurocognitive deficits in ADHD. Specifically, the inefficient registration of visual information by children with ADHD appears to slow the rate at which information becomes accessible within PHWM, resulting in a bottleneck that is likely compounded by the rapid degradation of information from the short-term store unless that information is actively rehearsed (Baddeley, 2007). In addition, the faster response time exhibited by children with ADHD appears to partially obfuscate detection of their PHWM difficulties. Collectively, it appears that the PHWM system in childhood ADHD is characterized by inefficient access and rapid degradation of information in the short-term store, decreased overall capacity (Martinussen et al., 2005), an impaired rehearsal mechanism (Bolden et al., 2012), and an underdeveloped central executive responsible for higher order processing of information held in the short-term storage system (Kasper et al., 2012). The extent to which lower level information-processing deficits exert their effect on the phonological storage/rehearsal system relative to the domain-general central executive is unknown, but warrants scrutiny given the involvement of PHWM across a range of learning outcomes (Sarver et al., 2012).

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Notes

1. For an exception, see Li et al. (2009).
2. All participants met criteria for ADHD-Combined Presentation based on *Diagnostic and Statistical Manual of Mental Disorders* (5th ed.; *DSM-5*; American Psychiatric Association, 2013) diagnostic criteria.
3. Scores for two typically developing (TD) children exceeded 1.5 SDs on one of the two parents', but not teachers', rating scales. Parent interview revealed no significant ADHD symptoms or symptoms associated with other clinical disorders for both children. Three children with ADHD had subthreshold scores on teacher-rated hyperactivity/impulsivity. Follow-up clinical interviews, however, indicated the subthreshold symptoms were attributable to substantial psychostimulant effects for two of the children while they were rated, and that all three children demonstrated a history of significant, persistent levels of hyperactivity/impulsivity and current impairment.

4. Phonological working memory (PHWM) performance data for a subset of the sample have been used in separate studies to evaluate conceptually unrelated hypotheses (e.g., Kofler et al., 2014; Rapport et al., 2008; Raiker, Rapport, Kofler, & Sarver, 2012). We have not previously reported the Picture Naming, Picture Reaction Time (RT), and Motor Speed data for any children in the current sample.
5. Briefly, the wider 95% confidence interval increases the likelihood that the confidence interval for c′ will include 0.0, indicating that diagnostic status and the dependent variable are no longer related significantly after accounting for the mediator (i.e., full mediation in Baron & Kenny, 1986, terminology). In contrast, the narrower 90% confidence interval is less likely to include 0.0, and therefore is likely to result in a more conservative conclusion regarding the magnitude of the relation between diagnostic status and the dependent variable after accounting for the mediator (i.e., partial mediation). For discussion and specific examples of this phenomenon, see Shrout and Bolger (2002).
6. Computed as the raw difference in milliseconds between each group's mean response time on the Picture Naming and Picture RT tasks, based on the methodological rationale presented earlier (ADHD = 586.37 ms, TD = 466.79 ms).

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