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# Reading Comprehension in Boys with ADHD: The Mediating Roles of Working Memory and Orthographic Conversion

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**Abstract** Reading comprehension difficulties in children with ADHD are well established; however, limited information exists concerning the cognitive mechanisms that contribute to these difficulties and the extent to which they interact with one another. The current study examines two broad cognitive processes known to be involved in children's reading comprehension abilities—(a) working memory (i.e., central executive processes [CE], phonological short-term memory [PH STM], and visuospatial short-term memory [VS STM]) and (b) orthographic conversion (i.e., conversion of visually presented text to a phonological code)—to elucidate their unique and interactive contribution to ADHD-related reading comprehension differences. Thirty-one boys with ADHD-combined type and 30 typically developing (TD) boys aged 8 to 12 years ($M = 9.64$, $SD = 1.22$) were administered multiple counterbalanced tasks assessing WM and orthographic conversion processes. Relative to TD boys, boys with ADHD exhibited significant deficits in PH STM ($d = -0.70$), VS STM ($d = -0.92$), CE ($d = -1.58$), and orthographic conversion ($d = -0.93$). Bias-corrected, bootstrapped mediation analyses revealed that CE and orthographic conversion processes modeled separately mediated ADHD-related reading comprehension differences partially, whereas PH STM and VS STM did not. CE and orthographic conversion modeled jointly mediated ADHD-related reading comprehension differences fully wherein orthographic conversion's large magnitude influence on reading comprehension occurred indirectly through CE's impact on the orthographic system. The findings suggest that adaptive cognitive interventions designed to improve reading-related outcomes in children with ADHD may benefit by including modules that train CE and orthographic conversion processes independently and interactively.

**Keywords** Attention-deficit/hyperactivity disorder · Reading comprehension · Working memory · Orthographic conversion · Executive functions

Attention-deficit/hyperactivity disorder-combined type (ADHD) is an early onset, neurodevelopmental disorder characterized by clinically impairing levels of inattention, hyperactivity, and impulsivity (American Psychiatric Association 2013). The disorder affects an estimated 3.5 million children in the United States (U.S. Census Bureau 2013) at an annual cost of approximately $51 billion based on current cost of illness estimates (Pelham et al. 2007). A preponderance of these costs are associated with the numerous learning difficulties experienced by children with ADHD-combined type (cf. Barkley 2007, for a review), many of which increase the risk of learning disabilities, wherein comorbidity averages are 45 % for any type of learning disability and 25 % for a specific learning disability in reading (DuPaul et al. 2013). Children with ADHD appear to be susceptible to reading related difficulties even in the absence of a comorbid reading disorder as evidenced by their lower scores on standardized reading tests (Frazier et al. 2007; Loe and Feldman 2007; Miller et al. 2012), classroom grades in reading (Loe and Feldman 2007), and productivity when engaged in reading related classroom activities (Rapport et al. 2009b; Ville Junod et al. 2006).

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Reading deficits in early education are of particular concern given that *learning to read* is a requisite and critically important precursor for *reading to learn* as children progress from elementary through high school. They also portend multiple adverse outcomes including later reading difficulties (McGee et al. 2002), delinquent behavior (Bennett et al. 2003; Maughan et al. 1985), and lower high school graduation rates (McGee et al. 2002). In later years, early reading deficits are associated with lower college matriculation and graduation rates (Murray et al. 2000), occupational instability (Maughan et al. 1985), and lower socioeconomic status (Murray et al. 2000).

Two primary cognitive systems have been examined in attempts to explicate reading comprehension difficulties in children—viz., working memory (WM) and orthographic conversion. WM is a multi-component system responsible for the storage, rehearsal, maintenance, processing, updating, and manipulation of internally held phonological and visuospatial information (Baddeley 2007). Extant evidence supports a tripartite model of WM (Baddeley 2007). The hierarchical *working* component consists of a domain-general, central executive (CE) attentional controller localized primarily in the prefrontal cortex that reacts to attentional/multi-task demands, provides an interface between WM and long-term memory, and is responsible for the oversight and coordination of two anatomically distinct *memory* subsystems (i.e., phonological short-term memory [PH STM] localized in the left temporoparietal region and Broca's area, and visuospatial short-term memory [VS STM] localized in the posterior parietal and superior occipital cortices; Baddeley 2003; Todd and Marois 2005). WM deficits in children with ADHD are well documented in meta-analytic reviews (Kasper et al. 2012; Martinussen et al. 2005; Willcutt et al. 2005), and larger magnitude CE deficits relative to storage subsystem processes are uniformly reported for children with ADHD (Kofler et al. 2010; Rapport et al. 2008a).

WM deficiencies are associated commonly with reading comprehension difficulties in children with and without ADHD due to the multiple, interacting WM processes involved in identifying words and converting them into meaningful information during oral and covert reading (cf. Savage et al. 2007; Swanson and Alloway 2012). Specifically, visually presented reading material must be orthographically converted to a phonological code (Baddeley 2007). Once encoded, read information is stored temporarily in the capacity-limited PH STM subsystem whereupon multiple, interacting CE processes (a) determine the task-relevance of the internally-held information; (b) update information in PH STM with newer, more relevant information; (c) connect read information with knowledge stored in long-term memory; (d) maintain the overall 'gist' of read material; and (e) sustain attentional focus while concomitantly inhibiting irrelevant information from entering/competing with temporarily stored information (Finn et al. 2014; Gathercole et al. 2006; Swanson and Alloway 2012; see Fig. 1).

Extant experimental evidence indicates that the CE and the PH STM subsystem make significant, independent contributions to children's overall reading comprehension abilities (Swanson and Alloway 2012; Titz and Karbach 2014). In contrast, evidence for the role of VS STM in reading comprehension (e.g., facilitating the visual representation of read information in the mind; Swanson and Sachse-Lee 2001) is equivocal with some (Pham and Hasson 2014; St Clair-Thompson and Gathercole 2006) but not all studies (O'Shaughnessy and Swanson 1998; Swanson and Howell 2001) showing small to moderate magnitude relations with overall reading comprehension abilities.

Despite the large magnitude WM deficits identified in children with ADHD and well-established relations between WM and reading comprehension, few studies have examined the possible mechanisms that mediate ADHD-related reading comprehension difficulties and whether they reflect underdeveloped, domain general, higher-order CE processes and/or inadequate PH/VS STM capacity. One study reported that PH WM (i.e., CE and PH STM in tandem) and semantic language fully mediated the relationship between ADHD symptoms and reading achievement (Gremillion and Martel 2012). The mediating effect associated with the PH WM pathway was weak relative to the semantic language pathway; however, this finding must be viewed cautiously given the reliance on backward span tasks to estimate PH WM performance[1]. A second investigation reported full mediation of ADHD-related reading achievement deficits using a factor comprised of forward/backward digit span and serial reordering tasks (Rogers et al. 2011), whereas VS STM (forward and backward visual span tasks) did not. The unique contribution of the hierarchical CE and PH STM processes, however, were not examined but warrant scrutiny.

Another feasible explanation for ADHD-related reading comprehension deficits involves the initial encoding processes that translate visually presented text into phonological code (i.e., orthographic conversion), which may occur via a lexical/sight word or non-lexical/sounding out process. Successful orthographic conversion is incumbent upon upstream, CE-mediated processes that enable attentional control, inhibition of irrelevant information from entering the short-term store, and retrieval of stored words/phonemes from long-term memory (Kintsch 2007; McCutchen et al. 1991; see Fig. 1). These processes begin to become

[1] Studies by Rosen and Engle (1997) and others (e.g., Colom et al. 2005; Swanson and Kim 2007) provide compelling evidence that forward and backward simple digit span tasks load on a PH STM factor and are statistically separable from PH WM measures such as complex span tasks, the latter of which are more highly correlated with measures of children's reading competence.

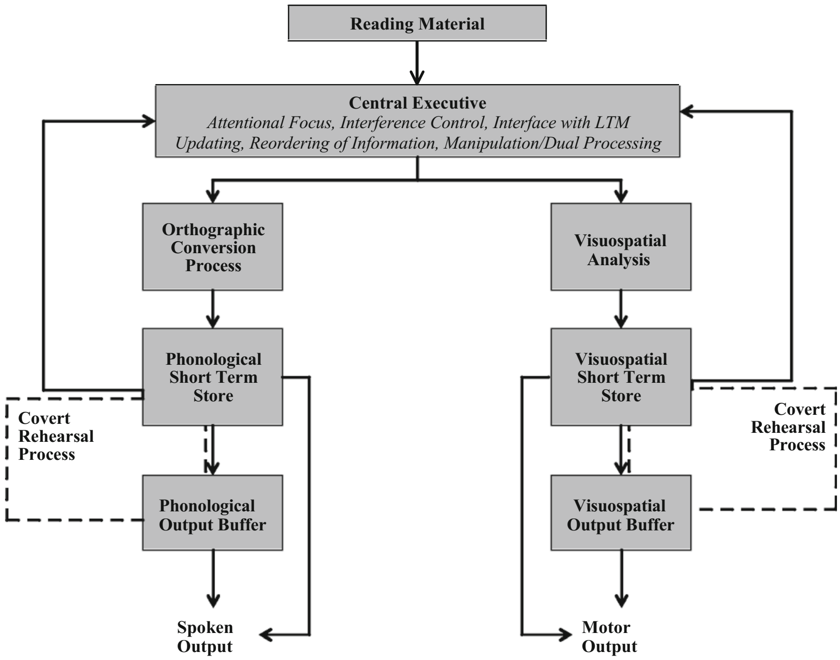


**Fig. 1** Adapted and expanded version of the Baddeley (2007) working memory model's involvement in reading comprehension

automatized at six years of age in most children (Guttentag and Haith 1978) at which time they require fewer CE resources to decode printed material. As a result, a greater proportion of CE processes can be allocated toward extracting meaning for passage comprehension (Perfetti et al. 2007; Swanson and Alloway 2012). If underdeveloped, deficient orthographic conversion processes may create a bottleneck whereby read information is slowed entering the downstream PH STM for successful meaning abstraction due to the increased CE demands necessary for this process (see Fig. 1).

Few investigations have examined the contribution of orthographic conversion ability in reading comprehension difficulties in boys with ADHD-combined type. An initial study reported significant reading comprehension deficits in children with ADHD relative to a control group matched on orthographic conversion ability, suggesting that orthographic conversion ability alone does not fully account for ADHD-related reading comprehension differences (Brock and Knapp 1996). A more recent investigation involving adolescents with and without ADHD (Guttentag and Haith 1978) pre-matched on word identification skills found that orthographic conversion ability was a partial mediator of reading comprehension difficulties after controlling for verbal and non-verbal IQ (Martinussen and Mackenzie 2015). The only study to date that included measures of PH WM in children pre-matched for orthographic conversion ability reported that PH WM fully mediated the relationship between ADHD symptomatology and the recall of central ideas from a read passage (Miller et al. 2013). The pre-matching procedure, however, introduces the potential confound of including a higher than expected percentage of control children with orthographic deficiencies given past findings of large-magnitude orthographic deficits among children with ADHD ($d = 0.92$, Stern and Shalev 2013).

Collectively, past investigations indicate that PH and VS STM alone play a limited role in understanding reading comprehension difficulties in children with attention problems, but that PH WM (i.e., CE and PH STM in tandem) and orthographic conversion abilities may independently or interactively contribute to ADHD-related reading comprehension difficulties. No study to date has fractionated the anatomically distinct CE from the PH and VS STM subsystems while concomitantly examining the potential contribution of orthographic conversion to ascertain their unique relations to ADHD-related reading comprehension difficulties. Moreover, the potential bottleneck effect of information entering PH STM caused by slowed and/or inaccurate orthographic conversion abilities warrants particular scrutiny. Elucidating the processes involved and extent to which they singly or interactively contribute to ADHD-related reading comprehension difficulties has potentially important implications for the design of efficacious remedial and/or preventative interventions for these children.

The lower level, modality-specific, short-term memory subsystems (PH STM and VS STM) were hypothesized to have limited or nonsignificant roles, whereas higher level CE and orthographic conversion processes were hypothesized to serve as significant, partial mediators of ADHD-related reading comprehension differences when modeled separately based on extant literature. Additionally, a serial mediator pathway involving orthographic conversion and PH STM was hypothesized as a partial mediator. If supported, this finding would suggest that ADHD-related reading comprehension differences partially reflect a bottleneck in the flow of information into PH STM caused by inefficient orthographic conversion. A serial mediator model involving both CE and orthographic conversion processes was hypothesized to fully mediate ADHD-related reading comprehension differences and render their independent pathways (CE, orthographic conversion) non-significant based on evidence supporting the involvement and interaction of both processes in reading comprehension (Brock and Knapp 1996; Miller et al. 2013; Rogers et al. 2011; Swanson and Alloway 2012; see Fig. 1). If supported, this finding would indicate that the contributions of the independent processes (CE, orthographic conversion) are insufficient explanations to account for ADHD-related reading comprehension difficulties fully.

## Method

### Participants

The sample comprised 61 boys aged 8 to 12 years ($M = 9.64$, $SD = 1.22$), recruited by or referred to a children's learning clinic through community resources (e.g., referrals from pediatricians, community mental health clinics, school systems, and self-referral). Sample race and ethnicity included 43 Caucasian Non-Hispanic (69.4 %), 12 Hispanic English speaking (19.4 %), four bi- or multi-racial (6.5 %), and two African American (3.2 %) boys. All parents and children provided their informed consent/assent prior to participating in the study, and approval from the university's Institutional Review Board was obtained prior to the onset of data collection. Two groups of boys participated in the study: boys with ADHD ($n = 31$), and typically developing boys ($n = 30$) without a psychological disorder. Boys 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 < 85 were excluded.

### Group Assignment

All children and their parents participated in a detailed, semi-structured clinical interview using all modules of the Kiddie Schedule for Affective Disorders and Schizophrenia for School-Aged Children (K-SADS). The K-SADS assesses onset, course, duration, severity, and impairment of current and past episodes of psychopathology in children and adolescents based on DSM-IV criteria. Its psychometric properties are well established, including interrater agreement of 0.93 to 1.00, test-retest reliability of 0.63 to 1.00, and concurrent (criterion) validity between the K-SADS and psychometrically established parent rating scales (Kaufman et al. 1997).

Thirty-one boys meeting the following criteria were included in the ADHD-Combined Type group: (1) an independent diagnosis by the directing clinical psychologist using DSM-IV[2] criteria for ADHD-Combined Type based on K-SADS interview with parent and child; (2) parent ratings of at least 2 *SD*s above the mean on the Attention-Deficit/Hyperactivity Problems DSM-Oriented scale of the Child Behavior Checklist (CBCL; Achenbach and Rescorla 2001), or exceeding the criterion score for the parent version of the ADHD-Combined subtype subscale of the Child Symptom Inventory-4: Parent Checklist (CSI-P; Gadow et al. 2004); and (3) teacher ratings of at least 2 *SD*s above the mean on the Attention-Deficit/Hyperactivity Problems DSM-Oriented scale of the Teacher Report Form (TRF; Achenbach and Rescorla 2001), or exceeding the criterion score for the teacher version of the ADHD-Combined subtype subscale of the Child Symptom Inventory-4: Teacher Checklist (CSI-T; Gadow et al. 2004). The CBCL, TRF, and CSI are among the most widely used behavior rating scales for assessing psychopathology in children. Their psychometric properties are well established (Rapport et al. 2008b). Twelve (38.7 %) of the ADHD children were on a psychostimulant regimen for treatment of their ADHD symptoms (24-h washout period prior to each testing session), and seven (22.6 %) met diagnostic criteria for Oppositional Defiant Disorder (ODD).

Thirty boys 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 parental report; (3) ratings within 1.5 *SD*s of the mean on all CBCL and TRF scales; and (4) parent and teacher ratings within the non-clinical range on all CSI subscales[3].

### Procedures

The Orthographic Conversion Speed task and WM tasks (described below) were programmed using SuperLab Pro 2.0 (Cedrus Corporation 2002) and were administered as part of a larger battery that required the child's presence for approximately 3 h per session across four consecutive

[2] All participants met criteria for ADHD-Combined Type using DSM-5 diagnostic criteria.

[3] Scores for one TD child exceeded 1.5 *SD*s 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 the child. Seven 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 while they were rated, and that all children demonstrated a history of significant, persistent levels of hyperactivity/impulsivity both at home and at school.

Saturday assessment sessions. Participants completed all tasks while seated alone, approximately 0.66 m from a computer monitor, in an assessment room. Performance was monitored at all times by the examiner, who was stationed just outside the child's view to provide a structured setting while minimizing performance improvements associated with examiner demand characteristics (Power 1992). All participants received brief (2–3 min) breaks following each task, and preset longer (10–15 min) breaks after every two to three tasks to minimize fatigue. The Kaufman Test of Educational Achievement 1st or 2nd edition (KTEA-I-Normative Update; Kaufman and Kaufman 1998; KTEA-II; Kaufman and Kaufman 2004) was administered during two separate weekday testing sessions to minimize fatigue. The changeover to the second edition was due to its release during the study and to provide parents the most up-to-date educational evaluation possible.

## Measures

**Reading Comprehension Task** Age-corrected, standardized Reading Comprehension subtest scores from the KTEA-I-NU (Kaufman and Kaufman 1998) or KTEA-II (Kaufman and Kaufman 2004) served as the dependent variable to assess comprehension of the literal and inferential meaning of printed text ($r = 0.77$ between the two versions; Kaufman and Kaufman 2004). The subtest requires children to read increasingly complex printed passages and answer visually presented questions. The passage remains visible to the child while responding to the questions, and answers are provided orally to the examiner and recorded manually on a standardized sheet. The psychometric properties and expected patterns of relationships between the KTEA Reading Comprehension subtest and other measures of educational achievement are well established (cf. Kaufman and Kaufman 1998, 2004).

## Working Memory Tasks

The working memory tasks used in the current study are identical to those described by Rapport et al. (2008a)[4]. Each child was administered four phonological conditions (i.e., set sizes 3, 4, 5, and 6) and four visuospatial conditions (i.e., set sizes 3, 4, 5, and 6) across the four testing sessions. The four working memory set size conditions each contained 24 unique trials of the same stimulus set size, and were counterbalanced across the four testing sessions to control for order effects and potential proactive interference effects across set size conditions. Previous studies of ADHD and typically developing children reveal large magnitude between-group differences on these tasks (Rapport et al. 2008a). The WM tasks also have high internal consistency ($\alpha = 0.81$ to 0.95) in the current sample and the expected level of external validity ($r = 0.50$ to 0.66) with WISC-III and -IV Digit Span STM raw scores (Raiker et al. 2012).

**Phonological Working Memory (PH WM)** The PH WM tasks are similar to the Letter-Number Sequencing subtest on the WISC-IV (Wechsler 2003), and assess phonological working memory based on Baddeley's (2007) model. Children were presented a series of jumbled numbers and a capital letter on a computer monitor. Each number and letter (4 cm height) appeared on the screen for 800 ms, followed by a 200 ms interstimulus interval. The letter never appeared in the first or last position of the sequence to minimize potential primacy and recency effects, and trials were counterbalanced to ensure that letters appeared an equal number of times in the other serial positions (i.e., position 2, 3, 4, or 5). Children were instructed to recall the numbers in order from smallest to largest, and to say the letter last (e.g., 4 H 6 2 is correctly recalled as 2 4 6 H). Children completed five practice trials prior to each administration (≥80 % correct required). All children achieved the minimum of 80 % accuracy on training trials. Two trained research assistants, shielded from the participant's view, recorded oral responses independently. Interrater reliability was calculated for all task conditions for all children, and ranged from 0.97 to 0.99.

**Visuospatial Working Memory (VS WM)** Children were shown nine squares arranged in three offset vertical columns on a computer monitor. A series of 2.5 cm diameter dots (3, 4, 5, or 6) were presented sequentially in one of the nine squares during each trial such that no two dots appeared in the same square on a given trial. All but one dot that was presented within the squares was black; the exception being a red dot that never appeared as the first or last stimulus in the sequence. Children were instructed to indicate the serial position of black dots in the order presented by pressing the corresponding squares on a computer keyboard, and to indicate the serial position of the red dot last.

**Working Memory Factors** Estimates of the central executive (CE), phonological short-term memory (PH STM), and visuospatial short-term memory (VS STM) were computed at each set size using the procedures described by Rapport et al. (2008a). Briefly, the PH and VS systems are functionally and anatomically independent, with the exception of a shared (domain-general) CE controller (Baddeley 2007). Statistical regression techniques were consequently employed to provide reliable estimates of the controlling CE and its subsidiary PH and VS STM subsystems. The CE was estimated by

[4] PH WM and VS WM performance data for a subset of the current sample were used in separate studies to evaluate conceptually unrelated hypotheses (Alderson et al. 2010, 2012; Kofler et al. 2010, 2011, 2014; Raiker et al. 2012; Rapport et al. 2008a, 2009a; Sarver et al. 2015). We have not previously reported the reading comprehension or orthographic speed/accuracy data or their associations with our WM tasks for any children in the current sample.

regressing the lower-level subsystem processes onto each other based on the assumption that shared variance between the two measures (PH WM, VS WM) reflects the domain-general, higher-order supervisory mechanism for the two processes. The two predictor scores were averaged subsequently to provide an estimate of the CE. Removing the common variance of the PH and VS subsidiary systems has the additional advantage of providing residual estimates of PH and VS functioning independent of CE influences. Precedence for using shared variance to statistically derive CE and/or PH/VS STM variables is found for working memory components in Colom et al. (2005), Engle et al. (1999), Kane et al. (2004), Rosen and Engle (1997), and Swanson and Kim (2007). Factors were created for each construct (CE factor loadings = 0.89 to 0.94; PH factor loadings = 0.54 to 0.71; VS factor loadings = 0.58 to 0.80) using scores averaged across each of the four set sizes.

### Orthographic Conversion Tasks

**Orthographic Conversion Speed** 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 a written instruction (i.e., "PRESS SPACEBAR TO BEGIN"). Children were instructed to read the story aloud and re-press the spacebar when they reached the last word on the page (END). The time of passage completion served as an indicator of orthographic conversion speed.

**Orthographic Conversion Accuracy** Age-corrected, standardized subtest scores from the Reading Decoding subtest of the KTEA-I-NU (Kaufman and Kaufman 1998) and the Letter & Word Recognition subtest of the KTEA-II (Kaufman and Kaufman 2004) were used to measure the extent to which children were able to orthographically convert printed text accurately ($r = 0.84$ between the two versions; Kaufman and Kaufman 2004). Both versions of the task require children to orally pronounce printed single words of increasing complexity. The psychometric properties (Kaufman and Kaufman 1998, 2004) and expected patterns of relationships with other measures of orthographic conversion are well established (e.g., $r = 0.84$ between KTEA-I and PIAT Reading Recognition subtest; $r = 0.79$ between KTEA-II and WIAT-II Word Reading subtest).

**Orthographic Conversion Dependent Factor** A factor score reflecting an estimate of overall orthographic conversion ability was created using the Orthographic Conversion Speed Task and Orthographic Conversion Accuracy Task, as described in Miller et al. (2013). The Orthographic Conversion Speed Task raw scores were multiplied by (−1), such that higher scores indicate better orthographic conversion abilities across both the accuracy and speed tasks. The Orthographic Conversion factor was derived via principle components factor analysis (factor loadings = 0.88; eigenvalue = 1.5) to reflect shared orthographic conversion ability between the two tasks.[5]

**Measured Intelligence** Children were administered the WISC-III or -IV to obtain an overall estimate of intellectual functioning based on each child's estimated Full Scale IQ (FSIQ; Wechsler 2003). The changeover to the fourth edition was due to its release during the course of the study and to provide parents with the most up-to-date intellectual evaluation possible.

## Results

### Power Analysis

A large magnitude effect size was predicted based on established relations between ADHD and WM ($d$s = 1.89, 2.31; Rapport et al. 2008a), between ADHD and orthographic conversion ($d = 0.92$; Stern and Shalev 2013), between WM and reading comprehension ($r = 0.57$-$0.58$; Swanson and Jerman 2007), and orthographic conversion and reading comprehension ($r = 0.64$, Kaufman and Kaufman 2004). Mediation analysis using bias-corrected bootstrapping requires 34 total participants to achieve 0.80 power (Fritz and MacKinnon 2007), and 61 boys participated in the current study.

### Preliminary Analysis

All independent and dependent variables were screened for multivariate outliers using Mahalanobis distance tests ($p < 0.001$) and univariate outliers as reflected by scores exceeding 3.5 standard deviations from the mean in either direction (Tabachnick and Fidell 2007). One child with ADHD was identified as an outlier on the Orthographic Conversion Speed task. The raw score was replaced with 1 unit (second) greater than the next most extreme score as recommended by Tabachnick and Fidell (2007). Missing data represented 0.09 % of available data points due to the non-administration of the Orthographic Conversion Speed task for one child, and was replaced with the ADHD group mean as recommended (Tabachnick and Fidell 2007). The exclusion or inclusion of this case did not change the pattern of results.

As expected, scores on the parent and teacher behavior rating scales were significantly higher for the ADHD group relative to the typically developing group (see Table 1).

[5] The N-to-K ratio of 61:2 was within recommended guidelines for deriving the Orthographic Conversion variable (Hogarty et al. 2005).

**Table 1** Sample and Demographic Variables

| Variable | ADHD | | Typically Developing | | | |
|---|---|---|---|---|---|---|
| | $\bar{X}$ | *SD* | $\bar{X}$ | *SD* | *F* | Cohen's *d* |
| Age | 9.35 | 1.06 | 9.94 | 1.32 | 3.73 | −0.49 |
| FSIQ | 104.19 | 10.31 | 111.23 | 11.82 | 6.16* | −0.64 |
| FSIQres | −0.04 | 0.94 | 0.04 | 1.06 | 0.08 | −0.08 |
| SES | 48.58 | 11.07 | 52.81 | 10.09 | 2.43 | −0.40 |
| CBCL AD/HD Problems | 72.39 | 7.29 | 53.33 | 6.76 | 111.84*** | 2.71 |
| TRF AD/HD Problems | 67.10 | 7.67 | 51.30 | 10.78 | 43.73*** | 1.69 |
| CBCL Internalizing Problems | 61.74 | 8.93 | 49.10 | 11.22 | 23.77*** | 1.25 |
| TRF Internalizing Problems | 55.52 | 9.35 | 45.37 | 7.75 | 21.22*** | 1.18 |
| CSI-P: ADHD, Combined | 77.26 | 9.70 | 47.90 | 10.45 | 129.32*** | 2.91 |
| CSI-T: ADHD, Combined | 66.00 | 14.44 | 47.47 | 7.19 | 39.86*** | 1.62 |
| Reading Comprehension | 104.45 | 13.52 | 117.23 | 12.02 | 15.18*** | −1.00 |
| Phonological STM Factor Score | −0.32 | 1.10 | 0.34 | 0.76 | 7.34** | −0.70 |
| Visuospatial STM Factor Score | −0.41 | 0.97 | 0.43 | 0.85 | 12.93*** | −0.92 |
| Central Executive Factor Score | −0.61 | 0.90 | 0.63 | 0.65 | 37.90*** | −1.58 |
| Orthographic Conversion Factor Score | −0.42 | 1.13 | 0.43 | 0.62 | 13.08*** | −0.93 |

*ADHD* attention-deficit/hyperactivity disorder, *CBCL* Child Behavior Checklist, *CSI-P* Child Symptom Inventory: Parent severity *T*-scores, *CSI-T* Child Symptom Inventory: Teacher severity *T*-scores, *FSIQ* Full Scale Intelligence Quotient, *FSIQres* Full Scale Intelligence Quotient with working memory removed, *SES* socioeconomic status, *STM* short-term memory, *TRF* Teacher Report Form. * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$

Boys with ADHD and typically developing boys did not differ on age[6] ($p = 0.06$) or SES ($p = 0.12$). There was a small but significant between-group difference in FSIQ ($p = 0.02$). FSIQ was not analyzed as a covariate, however, because it shares significant variance with WM and would result in removing substantial variance associated with working memory from working memory (Dennis et al. 2009; Miller and Chapman 2001)[7]. Consistent with past studies (e.g., Rapport et al. 2008a), between-group differences in FSIQ were tested by removing reliable variance associated with CE (i.e., factor described above) from FSIQ and then examining between-group differences in FSIQ without the influence of CE. Results revealed that between-group differences in this residual FSIQ score were not significant ($p = 0.78$). As a result, simple model results with no covariates are reported to allow *B*-weights to be interpreted as Cohen's *d* effect sizes (Hayes 2009).

[6] Age was examined as a potential covariate given its trend towards significance and was a significant covariate for two of the mediators (CE and Orthographic Conversion) but not a significant covariate for any of the model's dependent variables. The marginal covariate effects did not affect the pattern or interpretation of results.

[7] Other alternative approaches, such as using a GAI, were considered but not adopted because the GAI shares considerable variance with WM (i.e. $r = 0.50$ to 0.63) and because VCI and PRI factor scores also share considerable variance with WM.

## Tier I: Intercorrelations

Intercorrelations between all factor scores were computed using bias-corrected bootstrapping with 90 % confidence intervals. All correlations for Tier II simple mediation models showed the expected relations (see Table 2); therefore, all three WM components and Orthographic Conversion were retained in Tier II.

## Tier II: Simple Mediation Analyses

Separate mediation models were tested to examine the extent to which each of the significantly related Tier I WM and orthographic conversion constructs attenuated the relationship between diagnostic status and reading comprehension abilities. All analyses were completed using bias-corrected bootstrapping to minimize Type II error as recommended by Shrout and Bolger (2002). Bootstrapping was used to establish the statistical significance of all total, direct, and indirect effects. All continuous variables were standardized *z*-scores based on the full sample to facilitate between-model 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

**Table 2** First-order correlations

| | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| 1. Diagnostic status (TD = 0, ADHD = 1) | | | | | |
| 2. Central Executive | −0.63*<br>(−0.73, −0.75) | | | | |
| 3. PH STM | −0.33*<br>(−0.52, −0.14) | 0.62*<br>(0.47, 0.73) | | | |
| 4. VS STM | −0.42*<br>(−0.59, −0.24) | 0.61*<br>(0.45, 0.75) | −0.24*<br>(−0.42, −0.05) | | |
| 5. Orthographic Conversion | −0.43*<br>(−0.55, −0.28) | 0.56*<br>(0.32, 0.73) | 0.23<br>(−0.01, 0.47) | 0.48*<br>(0.27, 0.64) | |
| 6. Reading Comprehension | −0.45*<br>(−0.61, −0.28) | 0.47*<br>(0.27, 0.63) | 0.30*<br>(0.07, 0.54) | 0.28*<br>(0.06, 0.48) | 0.72*<br>(0.61, 0.81) |

*ADHD* attention-deficit/hyperactivity disorder, *PH STM* phonological short-term memory, *TD* typically developing, *VS STM* visuospatial short-term memory. Correlations reflect bias corrected, bootstrapped Pearson's Correlation coefficients with 5000 samples derived from the original sample. Ninety percent confidence intervals are presented in parentheses below the corresponding correlation coefficient. *Correlation is significant based on confidence intervals that do not include 0.0 (Shrout and Bolger 2002)

(Hayes 2014) was used for all analyses and 5000 samples were derived from the original sample ($N = 61$) by a process of resampling with replacement (Hayes 2013; Shrout and Bolger 2002).

Effect ratios (indirect effect divided by total effect) were calculated to estimate the proportion of each significant total effect that was attributable to the mediating pathway (indirect effect). Cohen's $d$ effect sizes, standard errors, indirect effects, and effect ratios are shown in Figs. 2 and 3. Ninety percent confidence intervals were selected over 95 % confidence intervals because the former are more conservative for evaluating mediating effects (Shrout and Bolger 2002).[8]

**Total Effect** Examination of the total effect (Figs. 2 and 3 path c) revealed that Diagnostic Status (TD, ADHD) was related significantly to Reading Comprehension (Cohen's $d = -0.90$), such that boys with ADHD demonstrated large magnitude Reading Comprehension deficits prior to accounting for the potential mediating roles of Working Memory and Orthographic Conversion processes.

**Phonological Short-Term Memory Mediating ADHD Reading Comprehension Differences** A diagnosis of ADHD was associated with significantly poorer PH STM (Cohen's $d = -0.66$; Fig. 2a, path a); however, PH STM was not significantly related to Reading Comprehension independent of Diagnostic Status ($\beta = 0.17$; Fig. 2a, path b). Examination of the mediation pathway (Fig. 2a, path ab) revealed that the indirect effect of Diagnostic Status on Reading Comprehension (Cohen's $d = -0.11$; 90 % CI [−0.37, 0.03]) through its impact on PH STM was nonsignificant, indicating that PH STM is not a significant mediator of ADHD-related reading comprehension differences.

**Visuospatial Short-Term Memory Mediating ADHD Reading Comprehension Differences** A diagnosis of ADHD was associated with significantly poorer VS STM (Cohen's $d = -0.84$; Fig. 2b, path a); however, VS STM was not significantly related to Reading Comprehension abilities independent of Diagnostic Status ($\beta = 0.11$; Fig. 2b, path b). Examination of the mediation pathway (Fig. 2b, path ab) revealed that the indirect effect of Diagnostic Status on Reading Comprehension (Cohen's $d = -0.09$; 90 % CI [−0.32, 0.08]) through its impact on VS STM was nonsignificant, indicating that VS STM was not a significant mediator of ADHD-related reading comprehension differences.

**Central Executive WM Mediating ADHD Reading Comprehension Differences** A diagnosis of ADHD was associated with significantly poorer CE ability (Cohen's $d = -1.24$; Fig. 2c, path a), and CE ability was related significantly to Reading Comprehension abilities independent of

[8] Briefly, the wider 95 % confidence interval increases the likelihood that the confidence interval for c′ will include 0.0, indicating that diagnostic status and reading comprehension are no longer related significantly after accounting for the mediator (i.e., full mediation). 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 reading comprehension after accounting for the mediator (i.e., partial mediation). For discussion and specific examples of this phenomenon, see Shrout and Bolger (2002).

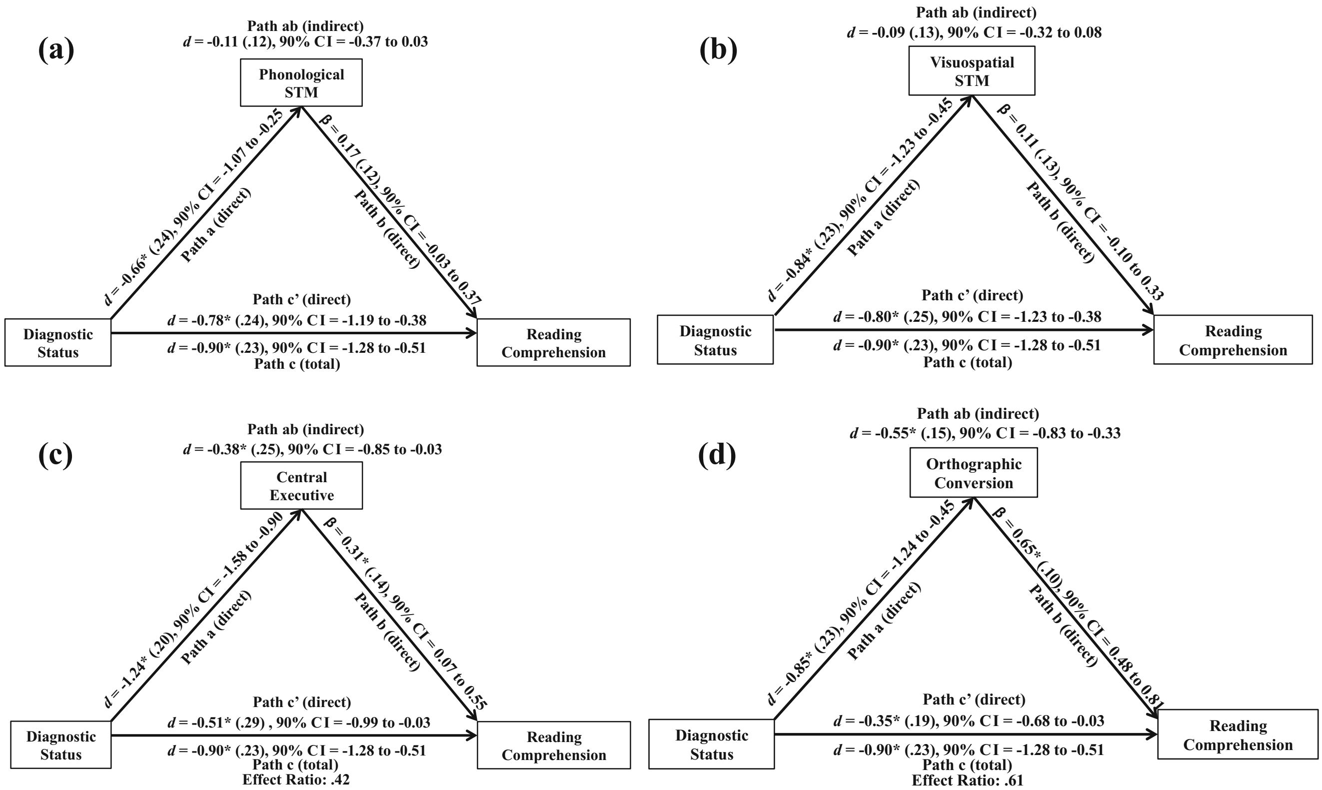


**Fig. 2** CI = confidence interval, STM = short-term memory. Schematics depicting the effect sizes, standard errors and $\beta$ coefficients of the total, direct, and indirect pathways for the mediating effect of (**a**) phonological short-term memory (**b**) visuospatial short-term memory, (**c**) central executive, and (**d**) orthographic conversion on reading comprehension. Cohen's $d$ for the c and c' pathways reflects the impact of ADHD diagnostic status on Reading Comprehension before (path c) and after (path c') taking into account the mediating variable. *Effect size (or $\beta$-weight) is significant based on 90 % confidence intervals that do not include 0.0 (Shrout and Bolger 2002); values for path b reflect $\beta$-weights due to the use of two continuous variables in the calculation of the direct effect

Diagnostic Status ($\beta = 0.31$; Fig. 2c, path b). Examination of the mediation pathway (Fig. 2c, path ab) revealed that Diagnostic Status exerted a significant, small to moderate magnitude indirect effect on Reading Comprehension (Cohen's $d = -0.38$; 90 % CI [−0.85, −0.03]) through its impact on CE, accounting for 42 % of the relation between Diagnostic Status and Reading Comprehension (Effect Ratio = 0.42). The relation between Diagnostic Status and Reading Comprehension remained significant after accounting for CE deficits ($d = -0.51$, 90 % CI [−0.99, −0.03]), indicating that CE was a partial mediator of ADHD-related reading comprehension differences.

**Orthographic Conversion Mediating ADHD Reading Comprehension Differences** A diagnosis of ADHD was associated with significantly poorer Orthographic Conversion ability (Cohen's $d = -0.85$; Fig. 2d, path a), and Orthographic Conversion was related significantly to Reading Comprehension abilities independent of Diagnostic Status ($\beta = 0.65$; Fig. 2d, path b). Examination of the mediation pathway (Fig. 2d, path ab) revealed that Diagnostic Status exerted a significant, moderate magnitude indirect effect on Reading Comprehension (Cohen's $d = -0.55$; 90 % CI [−0.83, −0.33]) through its impact on Orthographic Conversion ability and accounted for 61 % of the relation between Diagnostic Status and Reading Comprehension (Effect Ratio = 0.61). The relation between Diagnostic Status and Reading Comprehension remained significant after accounting for Orthographic Conversion ($d = -0.35$, 90 % CI [−0.68, −0.03]), indicating that Orthographic Conversion ability was a partial mediator of ADHD-related reading comprehension differences.

## Tier III: Serial Mediation Analyses

Taken together, the Tier II results indicate that CE and Orthographic Conversion accounted for 42 % and 61 % of the relation between diagnostic status and reading comprehension, respectively; however, neither fully attenuated between-group differences in reading comprehension. In the final analytic tier, we examined the extent to which the significant Tier II mediators (CE, Orthographic Conversion), alone and interactively, accounted for the between-group differences in reading comprehension by evaluating a serial multiple mediation model using the PROCESS script for SPSS (Hayes 2013). Only variables that significantly mediated the Diagnostic

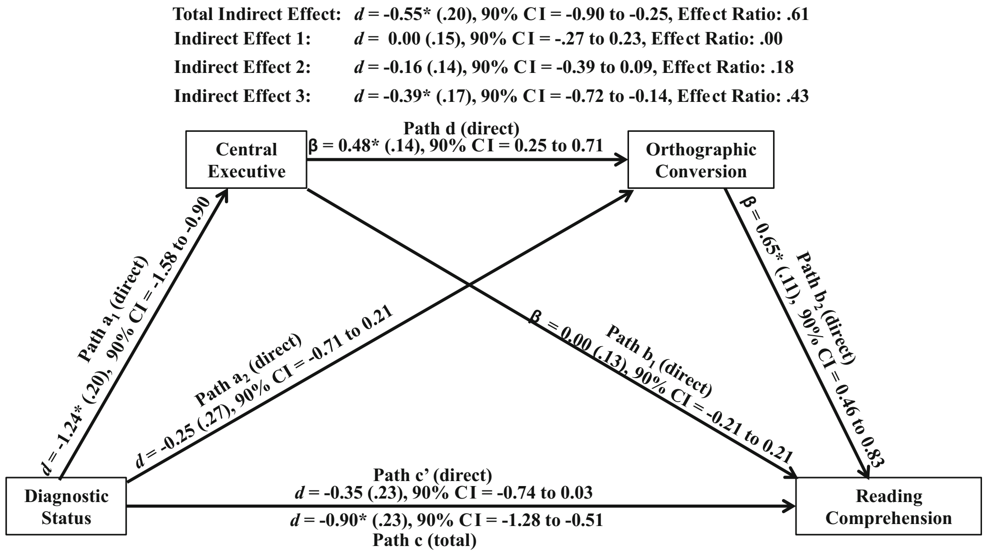


**Fig. 3** CI = confidence interval. Schematic depicting the effect sizes, standard errors, and $\beta$ coefficients of the total, direct, and indirect pathways for serial mediation of Central Executive and Orthographic Conversion on the relationship between Diagnostic Status and Reading Comprehension. Cohen's *d* for the c and c' pathways reflects the impact of ADHD diagnostic status on Reading Comprehension before (path c) and after (path c') taking into account the mediating variables. *Effect size (or $\beta$-weight) is significant based on 90 % confidence intervals that do not include 0.0 (Shrout and Bolger 2002); values for path b reflect $\beta$-weights due to the use of two continuous variables in the calculation of the direct effect. Indirect Effect 1 represents the mediating effect of Central Executive independent of Orthographic Conversion on Reading Comprehension. Indirect Effect 2 represents the mediating effect of Orthographic Conversion independent of the Central Executive on Reading Comprehension. Indirect Effect 3 represents the mediating effect of the shared influence of Central Executive and Orthographic Conversion on Reading Comprehension. Total Indirect Effect represents the collective influence of all three mediation pathways

Status to Reading Comprehension relation (i.e., CE, Orthographic Conversion) were retained in Tier III.

CE was entered into the model first based on theoretical grounds (Baddeley 2007) that CE-governed processes (e.g., attentional control, inhibition of irrelevant information from entering PH STM, and retrieval of stored words/phonemes from the long-term memory lexicon mechanism; Kintsch and Rawson 2007) are upstream of orthographic conversion processes, rather than vice versa. The serial mediation model provides three separate indirect effects. Indirect Effect 1 represents the proportion of the relation between Diagnostic Status and Reading Comprehension that is explained by the first mediator in the serial analyses, independent of the second. Indirect Effect 2 represents the proportion of the relation between Diagnostic Status and Reading Comprehension that is explained by the second mediator, independent of the first. Indirect Effect 3 represents the proportion of the relation between Diagnostic Status and Reading Comprehension that is explained by the shared influence of the two mediators. The Total Indirect Effect indicates the cumulative variance explained by all three indirect effects in the model.

The total effect of Diagnostic Status on Reading Comprehension ($d = -0.90$; Fig. 3, path c) was significantly attenuated when CE and Orthographic Conversion were included as mediators ($d = -0.35$; Fig. 3, path c'), such that the combined effect of all three mediating pathways accounted for 61 % of the ADHD/reading comprehension relation (Effect Ratio = 0.61) and the direct effect of Diagnostic Status on Reading Comprehension was no longer detectable (90 % CI included 0.0, indicating no effect). This combined effect was carried primarily by the mediating role of CE through its impact on Orthographic Conversion ($d = -0.39$; Effect Ratio = 0.43; Fig. 3, Indirect Effect 3) such that their joint influence explained 43 % of ADHD-related reading comprehension differences. Orthographic Conversion ability alone (i.e., independent of the influence of CE) did not significantly explain between-group differences in Reading Comprehension ($d = -0.16$; Effect Ratio = 0.18; 90 % CI included 0.0; Fig. 3, Indirect Effect 2) but accounted for a small proportion (18 %) of the relation between Diagnostic Status and Reading Comprehension. CE alone (i.e., independent of the influence of Orthographic Conversion) did not significantly explain between-group differences in Reading Comprehension ($d = 0.00$; Effect Ratio = 0.00; 90 % CI included 0.0; Fig. 3, Indirect Effect 1).

Notably, the combined effect ratios of CE through Orthographic Conversion (Effect Ratio = 0.43) and Orthographic Conversion independent of CE (Effect Ratio = 0.18) equal the effect ratio of Orthographic Conversion alone reported in Tier II as expected (i.e., 0.43 + 0.18 = 0.61). This finding indicates that Orthographic Conversion's large magnitude influence on Reading Comprehension occurs both directly and indirectly though

CE's impact on the orthographic system. Taken together with the high effect ratio (61 % of variance explained) and nonsignificant, residual association between Diagnostic Status and Reading Comprehension, these findings suggest that CE working memory deficits and downstream orthographic conversion difficulties explain the reading comprehension differences commonly observed among children with ADHD to a significant extent.

## Discussion

The current study is the first to fractionate the domain-general CE working memory processes from the anatomically distinct PH STM and VS STM subsystems while concomitantly examining orthographic conversion abilities to quantify their potentially unique and shared contributions to ADHD-related reading comprehension differences relative to typically developing children. Neither VS STM nor PH STM served as significant mediators of ADHD-related reading comprehension differences. The lack of a VS STM mediation effect was largely expected given the sparse (Swanson and Alloway 2012; Swanson and Howell 2001) or non-supporting (Rogers et al. 2011) literature regarding its involvement in children's reading comprehension abilities. Conversely, the nonsignificant PH STM mediation effect was somewhat unexpected based on extant research. For example, Rogers et al. (2011) reported full mediation of ADHD-related reading comprehension differences using a factor comprised of PH STM (forward/backward simple span) and CE processing (i.e., reordering) tasks. The distinct contributions of the CE and PH STM were not examined in the study, leaving unanswered whether one or both variables contributed to the significant mediation effect. Gremillion and Martel (2012) adopted a similar approach and reported partial mediation of the ADHD-related reading comprehension relation after accounting for PH STM (forward/backward simple span task performance), semantic language (WISC vocabulary), and non-verbal intelligence. Our regression-based approach for isolating CE from PH STM to minimize shared variance between the two variables (Engle et al. 1999), and the nonsignificant between-group differences in reading comprehension reported in the Gremillion and Martel (2012) study may have contributed to the discrepant findings across the two studies.

The higher order CE and orthographic conversion processes hypothesized to serve as mediators in the study each accounted for significant variance but only partially mediated ADHD-related reading comprehension difficulties when included as stand-alone variables. These findings corroborate those of previous investigations by demonstrating the influence of each process on children's reading comprehension abilities (Martinussen and Mackenzie 2015; Swanson and Alloway 2012), and their interweaved functions (McCutchen et al. 1991) substantiate examining the hypothesized interactions between the two processes. The results of the serial mediation model revealed that the two processes collectively mediated ADHD-related reading comprehension difficulties fully and likely reflect one or more cascading progressions. Based on extant literature, the most parsimonious explanation for the serial mediator finding is that deficient CE processes in children with ADHD weaken successful orthographic conversion of printed text due to (a) insufficient maintenance of attentional focus towards the text (McVay and Kane 2012); (b) inadequate inhibition of irrelevant information from entering the PH STM store (i.e., interference control; Palladino et al. 2001); and/or (c) slowed retrieval of stored words/phonemes from long-term memory (Kintsch and Rawson 2007; McCutchen et al. 1991). The unique and synergistic contributions of these processes likely places additional demands on available CE resources, and in turn, limit their availability for extracting knowledge during passage comprehension (Perfetti et al. 2007; Swanson and Alloway 2012). The measures employed in the current study did not allow for fractionation of distinct CE-related processes (i.e., focused attention, interaction with long-term memory, interference control, dual processing, and updating), and future investigations are needed to examine the relative contribution of separate and combined CE-mediated processes to elucidate their unique role(s) in understanding ADHD-related orthographic conversion and reading comprehension difficulties. Further, additional studies are needed to determine whether the lexical/sight-word and non-lexical/sounding-out route of reading decoding contribute differentially to reading difficulties in children with ADHD. Future investigations may also benefit from including multiple indicators of CE and orthographic conversion processes involved in reading comprehension (Shipstead et al. 2015).

Despite methodological (e.g., multiple tasks to estimate PH STM, VS STM, CE and orthographic conversion) and statistical (e.g., bootstrapped mediation) refinements, limitations are inherent to all research investigations. The exclusive inclusion of boys in the current study reflects the well-documented gender differences related to ADHD primary symptom prevalence and course (Gaub and Carlson 1997; Williamson and Johnston 2015), neurocognitive functioning (Bálint et al. 2009), and neural morphology (Dirlikov et al. 2015). Future studies, however, are likely to benefit from larger and more diverse samples that include females, younger children, and adolescents with ADHD, children with ADHD and comorbid Specific Learning Disability in Reading, and children with disorders where working memory performance deficits are suspected—e.g., depression (Harvey et al. 2004), anxiety (Tannock et al. 1995), and a wide range of developmental disabilities (Luna et al. 2002; Swanson and Sachse-Lee 2001). Despite recent reviews indicating that reading achievement and rates of Specific Learning Disorder in Reading are similar among children with ADHD-combined type and ADHD-inattentive type (Milich et al. 2001), future studies should evaluate whether the mediational influences of reading comprehension differ between the subtypes given the multiple neurocognitive differences identified (cf. Willcutt et al. 2005 for a meta-analytic review). Although the sample size of the current study exceeded recommended guidelines for detecting the expected magnitude of effects for the study design (Fritz and MacKinnon 2007; Shrout and Bolger 2002), we acknowledge that generalization to the broader ADHD population requires independent replication with larger samples to support the external validity of the findings.

Complementary fMRI/fNIRS neuroimaging and functional connectivity studies are also warranted to illuminate the neural networks implicated in ADHD-related reading comprehension difficulties and determine the extent to which neural connectivity deficits in regions attributed to executive control (prefrontal cortex) and the visual pathway/visual word form area (occipitoparietal cortices/fusiform gyrus) are similar to those identified in non-ADHD children with reading disability (Finn et al. 2014). This information, coupled with the findings associated with separable CE and orthographic conversion process performance tasks, can be used collectively to inform the design/development of reading comprehension training interventions and their associated clinical utility for children with ADHD.

Finally, the robust contributions of CE and orthographic conversion processes to children's reading comprehension abilities reflected in the current study have several potential clinical implications. This study is consistent with the strategic priorities of the NIMH RDoC and the emerging area of precision medicine suggesting that assessment of underlying cognitive abilities (e.g., orthographic conversion, central executive functioning) may improve existing treatments by identifying the cognitive deficits directly contributing to the development of reading comprehension abilities. Past interventions designed to strengthen executive functions in general, and WM in particular, have been relatively successful for improving PH STM and VS STM outcomes that are similar to those practiced during active training (i.e., near transfer effects). Small magnitude and nonsignificant findings, however, are reported consistently in well-controlled investigations examining far transfer effects[9] involving educationally relevant areas such as reading and math (Melby-Lervåg and Hulme 2013; Rapport et al. 2013). The results of the current investigation suggest that on-going efforts to design interventions to improve executive functions and/or WM processes that underlie and may generalize to academic abilities may benefit by including integrated, adaptive training modules designed to jointly strengthen CE and orthographic conversion processes consistent with their interactive nature. Additional research explicating which CE processes contribute significantly to reading comprehension differences in children with ADHD are needed to promote the development of training interventions; however, recent findings suggest that varying neurocognitive profile deficiencies among children with ADHD are the norm rather than the exception (Epstein et al. 2011; Willcutt et al. 2005), and suggest that cognitive training interventions will need to be personalized based on inter-individually identified strengths and weaknesses.

[9] Contemporary use of the terms *near transfer* and *far transfer* effects refers to an increase in performance on tasks that are highly similar and dissimilar to those used during training, respectively.

**Compliance with Ethical Standards**

**Conflict of Interest** The authors declare that they have no conflicts of interest.

**Funding** This study was conducted without external funding.

**Ethical approval** All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

**Informed consent** Informed consent/assent was obtained from all participants included in the study.

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