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Do Working Memory Deficits Underlie Reading Problems in Attention-Deficit/Hyperactivity Disorder (ADHD)?

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Abstract

Reading problems are common in children with ADHD and show strong covariation with these children's underdeveloped working memory abilities. In contrast, working memory training does not appear to improve reading performance for children with ADHD or neurotypical children. The current study bridges the gap between these conflicting findings, and combines dual-task methodology with Bayesian modeling to examine the role of working memory for explaining ADHD-related reading problems. Children ages 8–13 ($M = 10.50$, $SD = 1.59$) with and without ADHD ($N = 78$; 29 girls; 63% Caucasian/Non-Hispanic) completed a counterbalanced series of reading tasks that systematically manipulated concurrent working memory demands. Adding working memory demands produced disproportionate decrements in reading comprehension for children with ADHD ($d = -0.67$) relative to Non-ADHD children ($d = -0.18$); comprehension was significantly reduced in both groups when working memory demands were increased. These effects were robust to controls for foundational reading skills (decoding, sight word vocabulary) and comorbid reading disability. Concurrent working memory demands did not slow reading speed for either group. The ADHD group showed lower comprehension ($d = 1.02$) and speed ($d = 0.69$) even before adding working memory demands beyond those inherently required for reading. Exploratory conditional effects analyses indicated that underdeveloped working memory overlapped with 41% (comprehension) and 85% (speed) of these between-group differences. Reading problems in ADHD appear attributable, at least in part, to their underdeveloped working memory abilities. Combined with prior cross-sectional and longitudinal findings, the current experimental evidence positions working memory as a potential causal mechanism that is necessary but not sufficient for effectively understanding written language.

Keywords ADHD · Working Memory · Reading · Comprehension · Fluency · Bayesian

ADHD is a chronic and heterogeneous neurodevelopmental disorder that affects approximately 5% of school-aged children (Polanczyk et al. 2014) and is associated with impairments in peer, family, and academic functioning (Pelham et al. 2005) at an annual cost of illness of $42 billion in the U.S. (Pelham et al. 2007). Academically, 33% to 63% of children with ADHD demonstrate underachievement and learning difficulties in one or more academic domains (Mayes and Calhoun 2006). These academic difficulties have been documented across a broad range of ecologically-valid outcomes that include fewer assignments completed correctly (DuPaul et al. 1991), lower grade point averages, more failing grades, higher grade retention rates (Barkley 2006; Frazier et al. 2007), and lower standardized test scores (Frazier et al. 2007) despite greater access to special education remediation and accommodation services than their neurotypical peers (Biederman et al. 1996; Jensen et al. 2004; Loe and Feldman 2007). Longitudinally, ADHD symptoms predict lower teacher-reported (Diamantopoulou et al. 2007) and objectively-measured academic achievement (Sarver et al. 2012), independent of co-occurring conduct problems and IQ (Frick et al. 1991; Hinshaw 1992). Similarly, an ADHD diagnosis in childhood portends increased risk for high school drop-out and lower college entry and completion rates (Barkley et al. 2006; Mannuzza et al. 1997).

Understanding the mechanisms and processes responsible for the ADHD/underachievement link is critical given academic underachievement's association with myriad adverse

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social (Bickett and Milich 1990), economic, and occupational outcomes (Barkley et al. 2006). Longitudinally, early academic underachievement conveys risk for continued academic underachievement into middle school (Morrison et al. 2003) and high school (Chen et al. 1996; Sarver et al. 2012), increases risk for high school dropout (Finn et al. 2005), and predicts adult socioeconomic standing over 30 years later even after controlling for IQ and childhood SES (Ritchie and Bates 2013).

The reading-related difficulties exhibited by children with ADHD are particularly concerning given the high rates of comorbid reading disorders in ADHD (25%; DuPaul et al. 2013) and evidence of ADHD-related reading difficulties even in the absence of reading disability (Friedman et al. 2017; Ghelani et al. 2004). In addition, reading difficulties appear to be a critical component of early underachievement's longitudinal association with later behavioral problems (Bennett et al. 2003), later reading problems, high school dropout (McGee et al. 2002), and adult unemployment even after accounting for IQ and childhood behavior problems (Maughan et al. 1985).

Working Memory and Reading in ADHD

Working memory refers to the active, top-down manipulation of information held in short-term memory (Baddeley 2007), and includes interrelated functions of the mid-lateral prefrontal cortex and interconnected networks that involve dual-processing, supervisory attentional control, updating, and reordering (Nee et al. 2013; Wager and Smith 2003). Working memory is a particularly appealing executive function for understanding ADHD-related reading problems given its theoretical role in converting orthographic symbols to phonological sounds (decoding; Friedman et al. 2017) while manipulating and maintaining this information in a highly active state and accessing long-term memory to facilitate mental processing (Baddeley 2007). In addition, meta-analytic evidence indicates large magnitude working memory impairments in ADHD when measured using tasks with a prominent executive component (Kasper et al. 2012).

Emerging evidence points to executive dysfunction in general (Barry et al. 2002), and under-developed working memory in particular (Friedman et al. 2017; St Clair-Thompson and Gathercole 2006) as a candidate mechanism underlying reading underachievement in both community (Mayes and Calhoun 2006; Sarver et al. 2012) and ADHD samples (Friedman et al. 2017). For example, developmental evidence indicates strong cross-sectional (Sesma et al. 2009; Thorell 2007; Wåhlstedt et al. 2009) and longitudinal continuity between working memory and academic success in reading (Cain et al. 2004; Sarver et al. 2012), and meta-analytic evidence indicates significant working memory/reading associations across modality (i.e., visuospatial and phonological working memory) and reading skill (i.e., decoding, vocabulary, and comprehension; Peng et al. 2018). For children with ADHD, working memory dysfunction predicts concurrent reading underachievement (Kofler et al. 2016; Mayes and Calhoun 2006; Rogers et al. 2011) and longitudinally predicts reduced reading skills into young adulthood (Miller et al. 2012).

It has been suggested that working memory may explain the relation between ADHD and reading underachievement (Friedman et al. 2017). Understanding written language (i.e., reading) is a complex process that involves, at minimum, word recognition/decoding and an understanding of language (e.g., Lonigan 2015). Integral to the reading process, working memory provides the temporary storage and updating of information needed to integrate these word-reading and language processes to produce a level of comprehension (Perfetti et al. 2008), and has been linked with a broad range of reading skills including comprehension (e.g., Friedman et al. 2017), fluency (e.g., Jacobson et al. 2011), and decoding (e.g., Friedman et al. 2017). Thus, it is possible that children with ADHD have a higher rate of reading difficulties than their neurotypical peers due to their well-documented impairments in working memory (Kasper et al. 2012), either in conjunction with or as a mechanism underlying developmental deficits in word-reading/language. Results of studies examining the cognitive underpinnings of reading comprehension deficits in children with ADHD support this hypothesis, with working memory deficits consistently emerging as the only cognitive mechanism to mediate the ADHD/reading problem association, alone (Friedman et al. 2017; Miller et al. 2013) or in combination with semantic language skills (Gremillion and Martel 2012).

In contrast to the consistent findings linking working memory with reading, meta-analytic evidence indicates strongly that working memory training fails to significantly improve reading performance in children with ADHD (Rapport et al. 2013) and portends 'trivial' changes in reading performance in neurotypical samples ($d = 0.08$; Melby-Lervåg et al. 2016). A parsimonious explanation for this discrepancy may be that the working memory/reading association is caused or conveyed by third-variable processes that are not targeted by extant working memory training protocols (Rapport et al. 2013). However, the extent to which working memory's association with reading performance is causal remains unknown because, to our knowledge, the current evidence base relies exclusively on correlational methods that preclude strong conclusions. While longitudinal designs provide the strongest evidence of causality for constructs that cannot be manipulated experimentally (e.g., age), dual-task methodologies appear well-suited to address the extent to which working memory directly facilitates children's reading performance.

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Dual-task methodologies, which experimentally assess the extent to which increasing demands on a candidate causal process (working memory) disrupts performance on a hypothesized outcome of that process (reading), appear well-suited to address the extent to which working memory directly facilitates children's reading performance. This methodology relies on the limited capacity of human cognitive systems (e.g., Baddeley 2007), and allows strong conclusions regarding the extent to which mental processes compete for the same neurocognitive resources (Wang and Gathercole 2013). For example, finding that concurrent working memory demands disrupt reading performance would indicate that children rely, at least in part, on the same neurocognitive system for temporarily holding information (i.e., working memory) as they do for decoding and understanding written information (i.e., reading). In other words, this finding would indicate that processing written language for comprehension occurs at least in part within working memory (Wang and Gathercole 2013). In contrast, finding that children's reading performance is unaffected by concurrent working memory demands would indicate that reading and working memory rely on functionally distinct neurocognitive systems and lend strong support to the hypothesis that working memory's relation with reading performance is non-causal.

Current Study

Taken together, the literature at this time indicates (a) strong cross-sectional and longitudinal associations between working memory and reading performance in developmental and ADHD samples (Sarver et al. 2012; Miller et al. 2012), and that (b) reading-related impairments in ADHD may no longer be detectable after accounting for underdeveloped working memory abilities (Friedman et al. 2017). However, the majority of this literature has focused on correlational associations, whereas studies using intervention designs to assess causal relations have generally reported non-significant or minimal effects of working memory on reading performance in both ADHD and neurotypical samples (Melby-Lervåg et al. 2016; Rapport et al. 2013). One parsimonious hypothesis for this discrepancy may be that the working memory/reading relation is non-causal, in which case we would not expect working memory interventions to affect reading performance. The current study bridges the gap between these conflicting findings, and aims to provide the first experimental evidence to support or refute a causal role of working memory for explaining ADHD-related reading problems.

We used a series of four counterbalanced tasks to experimentally modify working memory processing demands while observing effects on children's reading comprehension and speed. Evidence supporting a causal role of working memory would be indicated by significant reductions in reading performance during the high working memory conditions relative to the otherwise identical, low working memory conditions. We further expected that children with ADHD would be disproportionately affected by this manipulation given their well-documented working memory deficits (e.g., Kasper et al. 2012). That is, we expected working memory demands that were equivalent in terms of cognitive load (i.e., number of to-be-recalled items) to be objectively more difficult and thus more disruptive to concurrent reading performance for children with ADHD given the availability of more limited working memory resources relative to Non-ADHD children (Kasper et al. 2012). In other words, we expected the experimental manipulation to be stronger when applied to children with ADHD due to their impairment on the manipulated ability.

Method

Participants

The sample included 78 children aged 8 to 13 years ($M = 10.50$, $SD = 1.59$; 49 boys, 29 girls) from the Southeastern United States, consecutively recruited by or referred to a university-based Children's Learning Clinic (CLC) through community resources (e.g., pediatricians, community mental health clinics, school system personnel, self-referral) between 2015 and 2017. The CLC is a research-practitioner training clinic known to the surrounding community for conducting developmental and clinical child research and providing pro bono comprehensive diagnostic and psychoeducational services. Its client base consists of children with suspected learning, behavioral or emotional problems, as well as typically developing children (those without a suspected psychological disorder) whose parents agreed to have them participate in developmental/clinical research studies. Psychoeducational evaluations were provided to all caregivers. All parents and children gave informed consent/assent, and Florida State University Institutional Review Board approval was obtained/maintained. Sample ethnicity was mixed with 49 Caucasian Non-Hispanic (63%), 11 African American (14%), 10 Hispanic (13%), 5 multiracial (6%), and 3 Asian American (4%) children.

Group Assignment

All children and caregivers completed an identical evaluation, regardless of recruitment/referral reason, that included detailed, semi-structured clinical interviewing (K-SADS; Kaufman et al. 1997). The K-SADS (2013 Update) assesses developmental history as well as onset, course, and impairment of DSM-5 (APA 2013) disorders in children and adolescents. Parent and teacher ADHD ratings were obtained from

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the Behavior Assessment System for Children (BASC-2; Reynolds and Kamphaus 2004) and Child Symptom Inventory (CSI-IV; Gadow and Sprafkin 2002).

Forty-one children met all of the following criteria and were included in the ADHD group ($n = 41$; 37% girls): (1) DSM-5 diagnosis of ADHD Combined ($n = 33$), Inattentive ($n = 6$), or Hyperactive/Impulsive Presentation ($n = 2$) by the directing clinical psychologist based on K-SADS; (2) Borderline/clinical elevations on at least one parent and one teacher ADHD rating scale; and (3) current impairment based on parent report. All ADHD subtypes/presentations were eligible given the instability of ADHD subtypes (Valo and Tannock 2010). Psychostimulants ($N_{prescribed} = 11$) were withheld ≥24 h for testing. Clinical consensus best estimate comorbidities include anxiety (24%), oppositional defiant (8%), depressive (5%), and high-functioning autism spectrum disorders (3%).[1] Given that co-occurring conditions are common in ADHD (Wilens et al. 2002), inclusion of children with these comorbidities was important to maximize external validity and generalizability of our findings.

The Non-ADHD group comprised 37 consecutive case-control referrals who did not meet ADHD criteria, and included both neurotypical children and children with psychiatric disorders other than ADHD. Neurotypical children (60%) had normal developmental histories and nonclinical parent/teacher ratings. Clinically-referred and evaluated children who did not meet ADHD criteria were also included in the Non-ADHD group. These Non-ADHD disorders were included to control for comorbidities in the ADHD group and account for performance patterns that may be driven by general psychopathology, rather than ADHD specifically. Best estimate diagnoses included anxiety (19%), high-functioning autism spectrum (10%), depressive (8%), and oppositional defiant disorders (3%).[1] Importantly, the ADHD and Non-ADHD groups were equivalent in the number of non-ADHD clinical disorders overall ($BF_{01} = 3.77$) and across diagnostic categories (omnibus: $BF_{01} = 19.62$; anxiety: $BF_{01} = 3.72$; depression: $BF_{01} = 6.10$; ASD: $BF_{01} = 2.59$; ODD: $BF_{01} = 5.59$). The Bayes Factor BF_{01} is an odds ratio indicating support for the null hypothesis that the groups are equivalent (H_0) relative to the alternative hypothesis that the groups differ (H_1) (see *Bayesian Analyses* section below).

Children were excluded for gross neurological, sensory, or motor impairment; history of seizure disorder, psychosis, or intellectual disability; or non-stimulant medications that could not be withheld for testing. Reading disability was defined based on score(s) >1.5 *SD* below age-norms on one or more KTEA-3 reading subtests, as specified in DSM-5 (APA 2013). The proportion of children with reading disability in the ADHD (13%) and Non-ADHD (3%) groups did not differ significantly ($BF_{01} = 2.31$). The influence of reading disability status on the pattern of results is described in the exploratory Tier 2 sensitivity analysis section below.

Procedure

Testing occurred during a larger battery of two, 3-h sessions. Tasks were counterbalanced within/across sessions to minimize order/fatigue effects. Children received brief breaks after each task, and preset longer breaks every 2–3 tasks to minimize fatigue.

Task Stimuli

The role of working memory deficits in children with ADHD's well-documented reading difficulties was assessed via four tasks counterbalanced across two testing days. As described below, two of these tasks were working memory complex span tasks, and the other two were control versions that were identical to their paired working memory variant but without the concurrent memory demands (Fig. 1). We included two control/working memory task pairs, counterbalanced across testing days, to address the 'task impurity' problem (Snyder et al. 2015), maximize effect certainty by controlling for within- and across-session error, and increase power via the addition of the within-subjects factor (task). Task stimuli were selected to provide robust manipulations of working memory's effects on reading performance while also providing control task data as part of a layered series of experiments designed to address secondary questions regarding emotion recognition and information processing in ADHD.

Animal/Animal Context Stimuli The animal and animal context stimulus categories were selected to allow these tasks to serve as robust controls for a matched series of experimental tasks assessing emotion recognition abilities in children with ADHD (reported in Wells et al., under review). The animal and animal context stimuli included six different animals (dogs, spiders, birds, fish, lions, and walruses). Each animal stimulus depicted a single exemplar of the target animal (Fig. 1, top left). Each animal context stimulus featured a scene that included a 'hidden animal' (depicted as a white circle with a black question mark) that could be inferred based on the rest of the picture (Fig. 1, top right). Forty high-quality, color exemplars of each animal/animal context were selected based on >90% correct identification by the study team.

Reading Stimuli The 196 true/false sentences from the Woodcock-Johnson Tests of Academic Achievement, Third Edition (WJ-III; Woodcock et al. 2001) Forms A and B reading fluency subtests were used to provide age-appropriate

[1] Results were unchanged when excluding children with autism spectrum disorders. As recommended in the K-SADS, oppositional defiant disorder was diagnosed clinically only with evidence of multi-informant/multi-setting symptoms. ODD comorbidity is 41% in the ADHD group and 9% in the Non-ADHD group based on parent-reported symptom counts.

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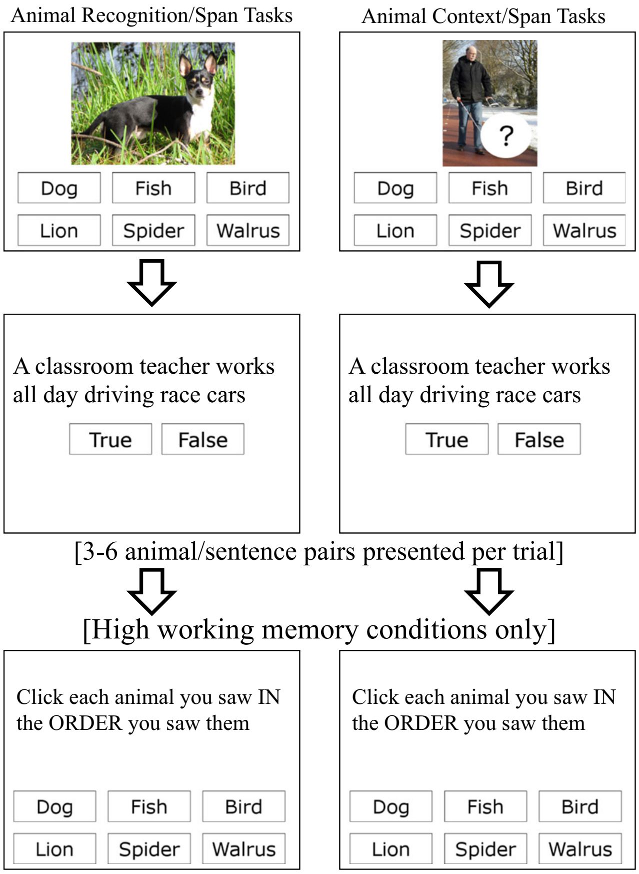

Fig. 1 Animal and animal context task variants. Each of the four counterbalanced tasks presented 36 randomly selected animals and sentences. Each low/high working memory task pair (animal recognition/animal span, animal context recognition/animal context span) was identical except for the omission or addition of concurrent working memory demands. Words/icons outside the six large boxes were not shown on screen, but are included here to illustrate differences across the four experimental task variants

silent reading material. Task instructions differed from the WJ-III and emphasized accurate responding rather than speed.

High Working Memory Conditions (Animal Span, Animal Context Span)

We created two variants of the reading span task described by Conway et al. (2005), adapted for use with children. Our animal and animal context working memory tasks both exemplify dual-processing working memory based on the Engle et al. (1999) model. These complex span tasks interleave the presentation of to-be-remembered target stimuli (animal names), with a demanding, secondary processing task (verifying sentences; Conway et al. 2005). Comparisons of ADHD and typically developing children indicate medium to large magnitude between-group differences on similar complex span tasks (Kuntsi et al. 2001; Willcutt et al. 2001). Evidence for reliability and validity of working memory complex span tasks includes high internal consistency ($\alpha = 0.77$ to 0.81), 3-month test-retest reliability of .70 to .80, and expected relations with other measures of working memory (Conway et al. 2005).

Eight total trials (2 trials per set size, set sizes 3–6, mixed presentation) were completed for each complex span task, with two practice trials administered prior to advancing to the full task (100% correct required). Serial position was a criterion for correct responses for both task variants. The primary task involved identifying and recalling animal names in the serial order presented. The secondary processing task involved silently reading and verifying sentences and was self-paced to allow measurement of children's reading comprehension and speed. Following Engle et al. (1999), children received performance feedback during both the primary and secondary task components.

Animal Span Children were sequentially shown screens containing a picture of a single animal at the top of the screen and six response boxes on the bottom of the screen (Fig. 1, left). Children were instructed to click the response box that matched the picture (e.g., clicking 'dog' when viewing a picture of a dog). After each animal, children silently read and responded to a true/false sentence by clicking the corresponding button on screen. After a predetermined number of animal-sentence pairs (set sizes 3, 4, 5, and 6), children were asked to recall the animals in serial order. The animals were presented first in each animal-sentence pair to ensure concurrent working memory demands during all sentence reading (Unsworth and Engle 2007).

Animal Context Span This task was identical to the animal span task, except that children had to infer which animal was hidden in each picture based on the context (Fig. 1, right).

Low Working Memory Conditions (Animal Recognition, Animal Context Recognition)

Animal Recognition and Animal Context Recognition Tasks These control tasks were identical to the animal span and animal context span tasks, respectively, except that children were not required to remember the animal names (i.e., the recall phase was omitted; Fig. 1, bottom). Children whose counterbalancing resulted in them completing either or both of these control tasks after the complex span variant(s) were explicitly told not to remember the animals.

Primary Outcomes: Reading Comprehension and Speed

Silent Reading Each task presented 36 randomly selected true/false sentences. Reading comprehension was indexed by the percent of correct responses to these sentences, separately for each of the four tasks. Reading speed was indexed as mean

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response time to these sentences (calculated separately for each of the four tasks), and is included in part to evaluate speed-accuracy tradeoffs when juxtaposed with the comprehension data. Of note, the broader literature often refers to reading speed within the context of optimal reading fluency (i.e., when speed is emphasized in the instructions; Pikulski and Chard 2005), whereas reading speed in the current study refers to children's silent reading rate when accuracy is emphasized.

Raw comprehension and accuracy scores for each of the four tasks were used in the Tier 1 and 2 models. The Tier 3 exploratory models were based on overall estimates of reading comprehension (71.71% variance accounted, loadings = .77–.91) and reading speed (69.43% variance accounted, loadings = .68–.91) computed using the dimension reduction approach described below.

Descriptive Outcomes: Working Memory Recall

Working Memory Complex Span Performance on the recall portions of the animal span and animal context span tasks were indexed by stimuli recalled correctly per trial at each set size, separately for both tasks (Conway et al. 2005). A dimension reduction approach was conducted to provide an overall estimate of each child's complex span working memory by computing a Bartlett weighted average based on the intercorrelations among task performance scores (DiStephano et al. 2009). These scores provide more accurate estimates of construct stability than confirmatory approaches (Willoughby et al. 2016). Conceptually, this process isolates "common and perfectly reliable variance" (Swanson and Kim 2007, p.158) associated with working memory complex span by removing task-specific demands associated with non-executive processes, as well as both short-term memory and time-on-task effects via inclusion of four set sizes per task. Thus, the 8 working memory complex span variables (set sizes 3–6 separately for animal span and animal context span; 38.14% of variance accounted) were reduced to a single estimate (loadings = .52–.71). Higher scores reflect better working memory.

Additional Reading Achievement

The Kaufman Test of Educational Achievement (KTEA-3; Kaufman and Kaufman 2014) is a nationally standardized and norm-referenced test of academic achievement. Selected reading-related subtests were used to probe the construct validity of our experimental reading measures and conduct sensitivity analyses. The KTEA-3 Reading Comprehension and Reading Fluency subtests were used to assess the construct validity of our experimental measures of reading comprehension and reading speed, respectively. In addition, the KTEA-3 Nonsense Word Decoding and Letter-Word Identification subtests were used to conduct sensitivity analyses and test the extent to which the primary findings were better accounted for by ADHD-related difficulties with decoding and sight word vocabulary, respectively. Standard Scores were obtained by comparing performance to the nationally representative standardization sample ($N = 3000$) according to age.

Additional Working Memory Tasks

The Rapport et al. (2009) working memory reordering tasks were used to evaluate the construct validity of our experimental working memory tasks, and to conduct exploratory analyses as detailed below. These tasks are described in the Supplemental Online section, and were selected to provide an independent estimate of working memory that is unrelated to phonological processing (i.e., to ensure that associations with reading cannot be attributable to reading demands during the working memory tasks; Friedman et al. 2017).

Intellectual Functioning (IQ) and Socioeconomic Status (SES)

IQ was assessed using the WISC-V Verbal Comprehension Index (Wechsler 2014). SES was estimated using the Hollingshead (1975) scoring based on caregiver(s)' education and occupation.

Bayesian Analyses

Bayesian analyses were selected because they allow stronger conclusions by estimating the magnitude of support for both the alternative and null hypotheses (Rouder and Morey 2012). That is, Bayesian methods can confirm the null hypothesis rather than just fail to reject it (Wagenmakers et al. 2016). Bayes factor mixed-model ANOVAs with JZS default prior scales (Rouder and Morey 2012; Wagenmakers et al. 2016) were conducted using JASP 0.8.2 (JASP Team 2017). Instead of a *p*-value, these analyses provide BF_{10}, which is the Bayes Factor of the alternative hypothesis (H_1) against the null hypothesis (H_0). BF_{10} is an odds ratio, where values above 3.0 are considered moderate evidence supporting the alternative hypothesis. BF_{10} values above 10.0 are considered strong (>30 = very strong, >100 = decisive/extreme support; Wagenmakers et al. 2016).

Conversely, BF_{01} is the Bayes Factor of the null hypothesis (H_0) against the alternative hypothesis (H_1). BF_{01} is the inverse of BF_{10} (i.e., $BF_{01} = 1/BF_{10}$), and is reported when the evidence indicates a lack of an effect (i.e., favors the null hypothesis; Rouder and Morey 2012). BF_{01} values are interpreted identically to BF_{10} (>3.0 = moderate, >10.0 = strong, >100 = decisive/extreme support for the null hypothesis that the ADHD and Non-ADHD groups are *equivalent* on an outcome; Rouder and Morey 2012).

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Between-group p-values are shown in Table 1 for comparison. Interpretation of results is unchanged if null hypothesis significance testing (NHST) is used instead of Bayesian analyses (except that non-significant p-values cannot be interpreted as evidence of equivalence).

Data Analysis Overview

We initially probed the construct validity of our experimental reading and working memory measures by correlating them with established tests of reading (KTEA-3; Kaufman and Kaufman 2014) and working memory (Rapport et al. 2008; Tarle et al. 2017), respectively. We then examined the study's primary hypotheses via Bayesian mixed-model ANOVAs to determine the extent to which experimentally increasing working memory demands disproportionately affected the ADHD group's reading performance as hypothesized (Tier 1). Tiers 2 and 3 were post-hoc analyses added to address questions that arose based on the Tier 1 results, and as such are labeled exploratory. In Tier 2, we conducted sensitivity analyses to examine the role of foundational reading skills (decoding, sight word vocabulary) on the Tier 1 findings, and determine the extent to which results were influenced by our decision to include children with reading disorder (Tier 2). Finally, in Tier 3 we used an independent estimate of working memory that was free of explicit reading-related demands to probe the Tier 1–2 finding that the ADHD group demonstrated impaired reading comprehension and speed across all task variants (i.e., the main effect of group that indicated performance differences even prior to adding additional working memory demands) (Tier 3 Exploratory Analyses, Supplementary Online).

Results

Bayesian Power Analysis

A series of simulation studies were conducted to estimate power for between-group tests using the R BayesFactor package and BayesianPowerTtest script (Lakens 2016) optimized by Zimmerman (2016), with parameters as follows ($N = 78$; r-scale = 1; $k = 100{,}000$ simulated experiments; BF threshold = 3.0). Results indicated power = .81 for supporting the alternative hypothesis of impaired reading performance in ADHD based on a true effect of $d = 0.74$ (meta-analytic estimate for ADHD/Non-ADHD reading differences from Frazier et al. 2007; 81% of simulations correctly supported H_1 at $BF_{10} \geq 3.0$, 18% provided equivocal support at BF_{10} values between 1/3 and 3, and only 1% incorrectly supported H_0). Similarly, results indicate that our Type 1 error probability is 1%. That is, we have a 1% chance of falsely supporting the alternative hypothesis if the null hypothesis is true (i.e., for $d = 0.0$; 77% of simulations supported H_0, 22% provided equivocal support, and only 1% incorrectly supported H_1). Taken together, the Bayesian power analyses indicate very low likelihood of drawing false conclusions, with a Type 1 false positive likelihood of 1% and a Type 2 false negative likelihood of 1%. Thus, the study is sufficiently powered to address its primary aims.

Preliminary Analyses

Outliers ≥ 3 *SD* were winsorized relative to the within-group distribution (ADHD, Non-ADHD; 11 of 1248 [0.9%] of data points). The ADHD group demonstrated impaired working memory on the complex span ($d = 0.74$, $BF_{10} = 19.09$), and Rapport et al. (2009) tasks ($d = 1.65$, $BF_{10} = 3.50 \times 10^7$) as expected. Construct validity of our reading comprehension and speed measures was supported by significant correlations with KTEA-3 reading comprehension ($r = .43$, $BF_{10} = 205.28$) and reading fluency ($r = -.33$, $BF_{10} = 4.77$), respectively. Similarly, the working memory complex span and reordering factors showed the expected level of covariation ($r = .49$, $BF_{10} = 2.59 \times 10^3$). The ADHD/Non-ADHD groups did not differ in age ($BF_{10} = 0.68$), gender ($BF_{10} = 0.28$), IQ ($BF_{10} = 1.29$), or SES ($BF_{10} = 2.10$); therefore, these variables were not included as covariates in the analyses below.

Tier 1 Primary Manipulation: Effects of Increasing Working Memory Demands on Reading Performance

Reading Comprehension The 2 (group: ADHD, Non-ADHD) × 2 (task: Animal, Animal Context) × 2 (working memory: Low, High) Bayesian mixed-model ANOVA indicated decisive evidence supporting main effects of group ($BF_{10} = 388.11$) and working memory ($BF_{10} = 2.37 \times 10^4$) on reading comprehension. In contrast, there was significant evidence of equivalence for task ($BF_{01} = 5.05$).

With reference to the significant main effects model, the evidence also significantly supported the addition of the group x working memory interaction ($BF_{10} = 7.90$). There was significant evidence against interactions of group x task ($BF_{01} = 4.91$), task x working memory ($BF_{01} = 5.00$), and the 3-way interaction ($BF_{01} = 70.86$).

As shown in Fig. 2 (top left), the group x working memory interaction was attributable to disproportionate decreases in reading comprehension for the ADHD group ($d = -0.67$; within-group $BF_{10} = 1244.83$) relative to the Non-ADHD group ($d = -0.18$; within-group $BF_{10} = 8.67$) when working memory demands increased. That is, reading comprehension deficits in ADHD became significantly more pronounced when working memory demands were higher.

Reading Speed The 2 (group: ADHD, Non-ADHD) × 2 (task: Animal, Animal Context) × 2 (working memory: Low, High) Bayesian mixed-model ANOVA indicated strong evidence supporting a main effect of group

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Table 1 Sample and demographic variables

Variable	ADHD ($n = 41$) *M*	*SD*	Non-ADHD ($n = 37$) *M*	*SD*	Cohen's *d*	BF_{10}	*p*
Gender (Girls/Boys)	15/26		14/23		–	0.28	.91, *ns*
Age	10.24	1.55	10.81	1.61	0.36	0.68	.12, *ns*
SES	45.43	12.78	51.60	10.87	0.52	2.10	*
WISC-V VCI	102.86	14.38	108.78	11.38	0.45	1.29	.05
KTEA-3 Reading Comprehension	97.42	12.69	104.29	12.67	0.54	2.35	*
KTEA-3 Letter-Word Identification	97.54	11.46	108.00	14.87	0.79	37.34	***
KTEA-3 Nonsense Word Decoding	93.76	15.92	106.00	12.98	0.84	50.21	***
KTEA-3 Silent Reading Fluency	95.80	12.57	101.85	15.22	0.44	1.07	.07, *ns*
BASC-2 Attention Problems (T-score)							
Parent	65.29	6.91	56.97	12.30	0.85	68.38	***
Teacher	64.39	7.57	52.53	10.14	1.34	>100	***
BASC-2 Hyperactivity Problems (T-score)							
Parent	68.45	13.11	54.78	11.75	1.09	>100	***
Teacher	63.50	15.09	53.61	12.39	0.71	14.14	**
CSI-IV Inattentive Symptom Quantity							
Parent	5.83	2.97	3.46	3.40	0.75	21.07	**
Teacher	5.73	2.87	2.57	3.12	1.06	>100	***
CSI-IV Hyperactive/Impulsive Symptom Quantity							
Parent	4.37	1.89	1.89	2.48	0.88	>100	***
Teacher	3.61	3.26	1.68	2.77	0.64	6.56	**
Reading Comprehension (% Correct)	*−0.42*	*1.15*	*0.49*	*0.42*	*1.02*	*>100*	***
Animal Recognition	0.93	0.06	0.98	0.03	0.90	>100	***
Animal Context Recognition	0.92	0.08	0.97	0.03	0.80	39.07	***
Animal Span	0.87	0.13	0.97	0.03	0.97	>100	***
Animal Context Span	0.88	0.13	0.95	0.04	0.71	12.94	**
Reading Speed (Seconds)	*0.31*	*1.14*	*−0.35*	*0.67*	*0.69*	*11.24*	**
Animal Recognition	7.29	2.35	5.91	1.45	0.70	12.59	**
Animal Context Recognition	7.65	2.55	6.52	1.37	0.55	2.73	*
Animal Span	7.35	2.67	6.36	1.56	0.45	1.23	.05
Animal Context Span	7.57	3.09	6.15	1.55	0.57	3.39	**
Working Memory Complex Span	*−0.31*	*1.10*	*0.39*	*0.70*	*0.74*	*19.09*	**
Animal Span 3	2.21	0.81	2.73	0.48	0.76	23.34	***
Animal Span 4	2.93	1.15	3.26	0.93	0.31	0.53	.18, *ns*
Animal Span 5	3.37	1.53	3.94	1.34	0.40	0.86	.09, *ns*
Animal Span 6	3.95	1.47	4.19	1.68	0.15	0.29	.52, *ns*
Animal Context Span 3	2.31	0.80	2.66	0.50	0.51	1.95	*
Animal Context Span 4	2.64	1.12	3.24	0.94	0.57	3.12	*
Animal Context Span 5	3.14	1.51	3.57	1.14	0.32	0.54	.17, *ns*
Animal Context Span 6	3.06	1.83	3.94	1.36	0.54	2.41	*

Note: Italicized rows indicate Bartlett component scores (z-scores). BF_{01} can be computed as the inverse of BF_{10} ($1/BF_{10}$). *P*-values are not corrected for family-wise error and are included for illustrative purposes to allow interested readers to compare Bayesian and frequentist results. BASC-2 = Behavior Assessment System for Children (T-scores); CSI-IV = Child Symptom Inventory; BF = Bayes Factor; KTEA-3 = Kaufman Tests of Educational Achievement (standard scores); SES = socioeconomic status; VCI = WISC-V Verbal Comprehension Index (IQ; standard scores)

$^{*}p \le .05$, $^{**}p \le .01$, $^{***}p \le .001$

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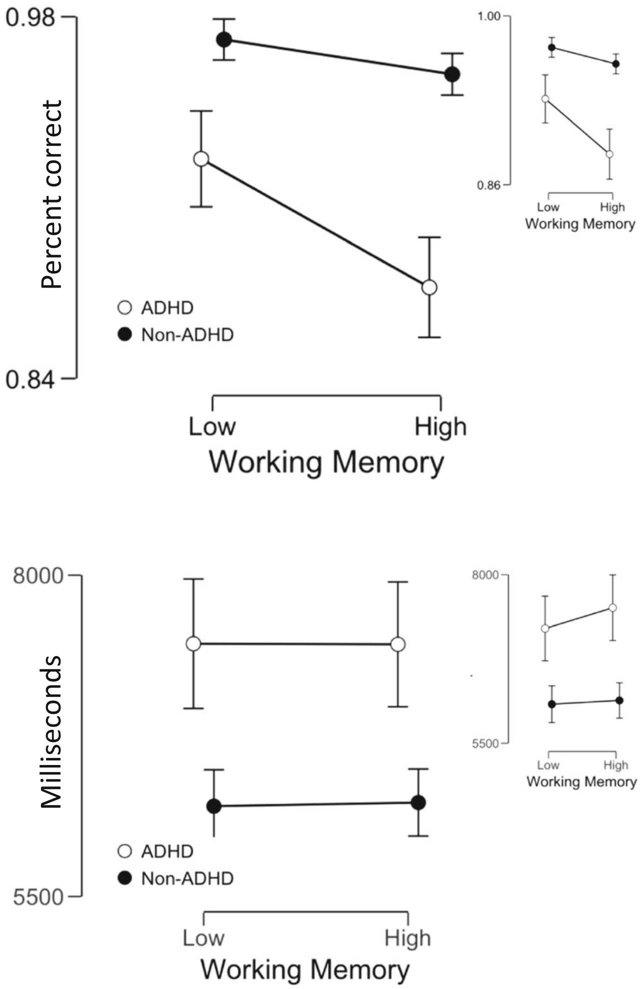

Fig. 2 Reading comprehension (top) and speed (bottom) as a function of group and concurrent working memory demands. Error bars reflect Bayesian 95% credibility intervals. Insets (right) reflect results when excluding children with comorbid reading disorder (ADHD $n = 5$, Non-ADHD $n = 1$)

($BF_{10} = 12.03$) on reading speed. In contrast, there was significant evidence against a main effect of working memory ($BF_{01} = 7.98$). Evidence also favored the null for task ($BF_{01} = 2.82$), but was insufficient to conclude that the tasks were equivalent.

With reference to the significant main effects model, there was strong evidence against interactions of group x working memory ($BF_{01} = 24.46$), group x task ($BF_{01} = 131.02$), task x working memory ($BF_{01} = 64.31$), and group x task x working memory ($BF_{01} = 2086.25$).

As shown in Fig. 2 (bottom left), these results indicate that increasing working memory demands did not affect reading speed for either the ADHD ($d = 0.002$) or Non-ADHD ($d = -0.01$) groups. That is, the impairment in reading speed for the ADHD group relative to the Non-ADHD group was highly similar during both the low ($d = 0.71$) and high ($d = 0.57$) working memory conditions.

Tier 2 Exploratory Sensitivity Analyses

Next, we conducted sensitivity analyses to assess the impact of subclinical difficulties with foundational reading skills (decoding and sight word knowledge), our decision to include children with a specific learning disorder in reading, and our decision to include children with clinical disorders other than ADHD in the Non-ADHD comparison group.

Effects of Reading Decoding and Sight Word Knowledge To probe the extent to which our findings were better attributable to difficulties with foundational reading skills rather than working memory, we repeated the Tier 1 primary analyses, this time covarying for reading decoding (KTEA-3 Nonsense Word Decoding) and sight word knowledge (KTEA-3 Letter-Word Identification). As expected, the ADHD group demonstrated less skill at decoding ($d = 0.84$, $BF_{10} = 50.21$) and sight word vocabulary ($d = 0.79$, $BF_{10} = 37.34$). In addition, both sight word knowledge ($BF_{10} = 2.10 \times 10^3$) and decoding skills ($BF_{10} = 9.98 \times 10^3$) predicted reading comprehension on our experimental tasks. However, controlling for these foundational reading skills did not attenuate the effects of working memory ($BF_{10} = 2.65 \times 10^4$), group ($BF_{10} = 7.74$), or the critical group x working memory interaction ($BF_{10} = 12.63$) effects on reading comprehension. Similarly, the pattern of significant and nonsignificant effects on reading speed did not change with decoding and sight word vocabulary covaried (e.g., main effect of group: $BF_{10} = 11.90$).

Taken together, these results support our claim that the experimental manipulation targeted working memory, and provide evidence that these effects were specific to reading comprehension and speed after accounting for the contribution of underlying foundation reading skills. In other words, reading comprehension became more difficult as working memory demands increased, and this effect remained even after accounting for the influence of variable decoding ability, indicating that working memory influenced not just the ability to identify and put together sounds to form words, but also to comprehend text quickly and efficiently.

Effects of Including Children with Specific Learning Disorder in Reading As specified in DSM-5, reading disorder was defined based on score(s) >1.5 *SD* below age-norms on one or more KTEA-3 Reading Composite subtests (13% of ADHD and 3% of Non-ADHD cases). As shown in Fig. 2b (insets), the pattern and interpretation of results was unchanged when excluding these children.

Effects of Including Children with Clinical Disorders Other than ADHD in the Non-ADHD Comparison Group As shown in the Supplementary Online section, the pattern and interpretation of results was unchanged when separating the neurotypical and clinical control cases into separate groups.

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The clinical and neurotypical groups were equivalent in terms of both reading accuracy ($BF_{01} = 7.12$) and reading speed ($BF_{01} = 4.08$).

Tier 3 Exploratory Analyses: Conditional Effects Modeling

A final set of analyses was conducted to follow up the Tier 1–2 findings that ADHD group status showed main effects on reading comprehension and speed. These exploratory analyses are detailed in the Supplementary Online materials, and involved testing the extent to which the omnibus between-group differences in reading comprehension and speed were related to the significant working memory demands inherent in reading (Wang and Gathercole 2013), irrespective of our manipulation that further increased these working memory demands. Separate models were run for reading comprehension and speed.

As detailed in the Supplementary Online analyses, ADHD status and working memory accounted for 25% of the variance in reading comprehension ($R^2_{total} = .25$). The Bayesian and frequentist results converged to indicate that there was no significant evidence supporting ADHD-related deficits in reading comprehension after accounting for working memory. Similarly, ADHD status and working memory accounted for 21% of the variance in reading speed ($R^2_{total} = .21$). The frequentist and Bayesian results converged to indicate that there was significant evidence refuting, and no significant evidence supporting, ADHD-related deficits in reading speed after accounting for working memory.

Discussion

The current study was the first to experimentally assess the extent to which the well-documented reading difficulties associated with ADHD (Kofler et al. 2016; Mayes and Calhoun 2007; Rogers et al. 2011; Willcutt et al. 2001) are attributable to impairments in working memory (Kasper et al. 2012). Overall, we replicated previous findings linking working memory deficits with reading difficulties in ADHD (Friedman et al. 2017), and extended prior work via an experimental manipulation that provides stronger evidence for causality. Importantly, increasing working memory demands disproportionately decreased reading comprehension for children with ADHD relative to a control group matched for comorbidities. The sensitivity analyses indicated that these findings could not be explained by variability in foundational reading skills such as decoding and sight word vocabulary. Taken together, these findings provide strong support for conceptualizing reading-related difficulties in ADHD as being caused, at least partially, by their working memory deficits (Kasper et al. 2012), particularly when combined with our exploratory conditional effects models indicating (1) robust associations between working memory and both reading comprehension and speed, even after accounting for ADHD status, and (2) ADHD and Non-ADHD between-group equivalence in reading speed after accounting for working memory. The use of Bayesian statistics allowed stronger conclusions because they provided evidence of between-group equivalence rather than just a lack of between-group differences (Wagenmakers et al. 2016).

Overall, children in both groups demonstrated poorer comprehension under higher working memory demands. Importantly, this manipulation produced significantly greater reading comprehension decrements in the ADHD ($d = -0.67$) versus Non-ADHD group ($d = -0.18$). These findings are consistent with replicated evidence of associations between working memory and reading comprehension in both ADHD and community samples (e.g., Christopher et al. 2012; Miller et al. 2013; Seigneuric and Ehrlich 2005) and offer support for the hypothesis that reading difficulties in children with ADHD are linked with their working memory deficits (e.g., Friedman et al. 2017). This interpretation is consistent with previous work indicating that children with ADHD read slower (Jacobson et al. 2011) and comprehend less (Brock and Knapp 1996) than their neurotypical peers. Juxtaposing working memory's effects on comprehension versus speed suggests that differential speed-accuracy trade-offs cannot explain why the Non-ADHD group was better able to maintain high levels of comprehension accuracy when faced with concurrent working memory demands.

Adding concurrent working memory demands failed to affect reading speed for both groups. At first glance, this finding appears inconsistent with correlational evidence suggesting significant relations between working memory and reading fluency for children with and without ADHD (e.g., de Carvalho et al. 2014). Notably, however, our correlational association between working memory and reading speed ($B = -0.43$; Supplementary Figure 1 bottom), and the ADHD group's impairment in reading speed ($d = -0.65$), were both highly consistent with expectations based on prior work (e.g., Jacobson et al. 2011). A possible explanation for this incongruence may be that, unlike prior work on this topic, the present study examined reading speed rather than reading fluency; thus, the current findings indicate that increasing working memory does not affect the rate at which children decode, process, comprehend, and respond to written text when comprehension accuracy is emphasized.

Notably, children in the ADHD group demonstrated slower and less accurate reading even during conditions with no added working memory demands. At first glance, this main effect of group appears contrary to our hypothesis that reading difficulties in ADHD are related to their underlying working memory deficits. To address this issue, we conducted

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exploratory analyses. Consistent with prior work, neither the Bayesian nor bias-corrected bootstrapping approaches were able to detect significant ADHD/Non-ADHD differences in reading comprehension after accounting for ADHD-related working memory impairments. Our findings were more conclusive for reading speed, such that the Bayes Factor indicated between-group equivalence (and not just a lack of significant differences). In other words, the slower rate at which children with ADHD decode, process, and respond to written text appears to be largely related to their underdeveloped working memory abilities. This conclusion is consistent with developmental evidence linking working memory with reading comprehension and fluency (Chrysochoou et al. 2011), and extends previous work by demonstrating this link in a new sample of children with and without ADHD matched for the number of non-ADHD disorders.

The current findings provide an initial step toward understanding the discrepancy between the large body of evidence linking working memory with reading comprehension (e.g., Chrysochoou et al. 2011) and the disappointing finding that working memory training fails to improve reading and other important academic outcomes in both ADHD (Rapport et al. 2013) and neurotypical samples (Melby-Lervåg et al. 2016). A parsimonious explanation for this discrepancy could have been that the working memory/reading association was correlational, and attributable to third-variable process(es) that are not targeted by extant working memory training protocols. The current results render this explanation unlikely, however, because we were able to evoke reductions in reading comprehension by increasing concurrent working memory demands.

Based on the current results, a more likely explanation relates to potentially unrealistic expectations regarding how much improving working memory should be expected to improve reading performance. Based on the meta-analytic estimate of $d=0.30$ for working memory training improving working memory in controlled studies of Non-ADHD samples ($d=0.28$–0.31; Melby-Lervåg et al. 2016), and our estimates of working memory's causal effect on reading comprehension for the Non-ADHD group ($d=0.18$), we would expect working memory training to portend reading comprehension improvements of $d=0.05$.[2] While highly similar to the $d=0.08$ meta-analytic effect of working memory training on reading comprehension reported for both neurotypical children (Sala and Gobet 2017) and adults (Melby-Lervåg et al. 2016), effects of this magnitude would require very large samples to detect and may have 'trivial' applied value (Melby-Lervåg et al. 2016).

Interestingly, the effect of working memory training on working memory maintenance in the ADHD literature is notably larger ($d=0.63$; Rapport et al. 2013), as are the current study's causal links between working memory and reading comprehension for these children ($d=0.67$). Combined with recent evidence that the working memory/reading link may be carried by working memory's role in orthographic decoding (Friedman et al. 2017), and that working memory training currently fails to improve academic outcomes for children with ADHD (Rapport et al. 2013), these findings suggest that (1) training effects may be detectable using more specific outcome measures, (2) efficacy may be maximized by creating training tasks that explicitly adapt working memory demands in the context of reading decoding tasks, and (3) optimal outcomes will likely require explicit skills-based reading instruction rather than working memory training alone (Chacko et al. 2014). Of course, these hypotheses are highly speculative because the current study manipulated but did not train working memory. As such, for clinical practice it currently appears prudent to recommend against extant working memory training protocols if the goal is to improve reading skills (Rapport et al. 2013; Roberts et al. 2016), particularly given the availability of efficacious evidence-based reading interventions (for review, see IES 2017).

Limitations

The current study was the first to experimentally link working memory deficits and underdeveloped reading skills in children with ADHD. Several caveats merit consideration despite this and other methodological refinements (e.g., Bayesian methods for testing between-group equivalence). Our experiment manipulated one piece of what is likely a more complex and interactive process, and as such explained a minority of the variance in children's reading comprehension and speed ($R^2=.21$–$.25$). Comprehending written text requires interrelated knowledge and skills that at a minimum include word-reading and language (Lonigan 2015). Future studies are needed to provide a more complete picture of the mechanisms that drive ADHD-related reading problems, toward development of a comprehensive remediation package that normalizes their reading skills.

As discussed above, our estimates of reading speed occurred within the context of tasks that emphasized accuracy rather than fluency; future work is needed to determine whether concurrent working memory demands produce speed-accuracy trade-offs as a function of different instructional sets or for more basic reading skills (e.g., decoding; Lonigan 2015). The percentage of children with ADHD prescribed psychostimulant medication in the current sample (27%) was somewhat lower than epidemiological estimates (Froehlich et al. 2007; Visser et al. 2014), and may be related to the psychoeducational evaluation provided to caregivers by our university-based clinic (i.e., inclusion of families seeking an initial evaluation).

[2] As discussed by Rapport et al. (2013), the maximum expected far transfer benefit can be estimated by multiplying the training effect by the association between working memory and the outcome. The estimated effect of 0.05 is based on multiplying the *SD* change in working memory by the *SD* change in reading comprehension attributable to working memory ($0.30 \times 0.18 = 0.05$).

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Given that co-occurring conditions are common in ADHD (Wilens et al. 2002), inclusion of children with these comorbidities was important to maximize external validity and generalizability of our findings. We attempted to balance external and internal validity threats by recruiting a Non-ADHD group matched for the number of these Non-ADHD disorders; however, controlling for the number of other disorders does not perfectly equate the groups, and as such future work is needed to compare more 'pure' ADHD and non-disordered samples. Similarly, inclusion of clinical disorders in the Non-ADHD group may limit conclusions regarding neurotypical reading skills, and we were unable to assess the extent to which the findings extend to children with low working memory but not ADHD (Holmes et al. 2014). Independent replications with larger samples, naturalistic outcomes, and a broader sampling of children with other clinical disorders are needed to assess the specificity of our results despite our finding that the manipulation produced comprehension decrements even in the Non-ADHD group. Finally, ADHD/Non-ADHD group differences were notably smaller during our complex span tasks ($d = 0.74$) than our working memory reordering tasks ($d = 1.65$). Given that the latter effect size is more consistent with meta-analytic estimates for working memory tasks with a prominent executive component (Kasper et al. 2012), our experimental manipulation may not have been as strong as intended despite evoking the hypothesized reading decrements.

Clinical and Research Implications

The current study builds on previous work in identifying working memory as a key mechanism underlying children's reading performance (Wang and Gathercole, 2013), and demonstrates that working memory demands disproportionately produce reading comprehension decrements for children with ADHD relative to their peers. Taken together, these findings indicate that children with ADHD demonstrate underdeveloped working memory abilities that explain, in part, their difficulties with reading quickly and accurately. These difficulties are compounded under conditions of higher working memory demands, which produce significant interference effects associated with trying to encode and process new information while retaining relevant previous information (Gathercole and Baddeley 2014), as might be seen when attempting to decode and comprehend longer and more complex sentences (such as this one). These findings may also provide an initial step in understanding why working memory training alone fails to improve reading comprehension in Non-ADHD and ADHD samples (Melby-Lervåg et al. 2016; Rapport et al. 2013), while providing promising data suggesting that the working memory/reading link may be at least partially causal and thus reading-related improvements may be theoretically possible – at least for children with ADHD.

Compliance with Ethical Standards

Conflict of Interest The authors have no conflicts of interest to report.

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 was obtained from caregivers of all individual participants included in the study.

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