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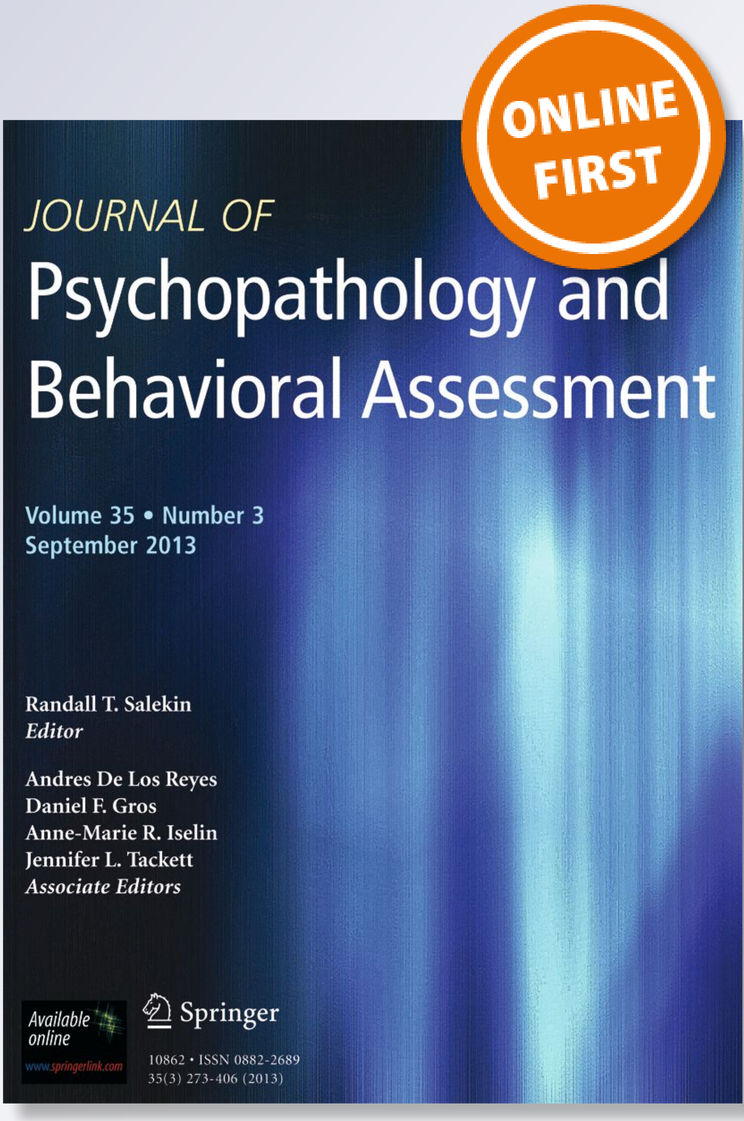

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IQ and Academic Achievement in Children with ADHD: the Differential Effects of Specific Cognitive Functions

Catrina A. Calub[1] · Mark D. Rapport[1] · Lauren M. Friedman[2] · Samuel J. Eckrich[1]

Abstract

The co-occurrence of lower full-scale intellectual abilities (FSIQ) and academic achievement deficits in children with ADHD is well established; however, the extent to which the relation reflects the influence of a general factor (*g*) deficiency or deficiencies in one or more specific intellectual abilities remains speculative and was the focus of the current investigation. Twenty-eight boys with ADHD-combined presentation and 26 neurotypical (NT) boys between 8 and 12 years of age were administered the WISC-IV and standardized measures of reading and math. FSIQ and achievement scores in both reading and math were significantly lower for the ADHD relative to the NT group; however, examination of WISC-IV index scores revealed that group level differences in FSIQ resulted from lower scores on two of the four specific intellectual ability indices—Working Memory (WMI) and Verbal Comprehension (VCI). Bias-corrected bootstrapped mediation analyses revealed that both WMI and VCI contributed uniquely to the ADHD-Academic Achievement relation. The contribution of WMI to ADHD-related academic underachievement reflected lower scores on the Letter-Number Sequencing (LNS) but not the Digit Span (DS) subtest. Both LNS and VCI explained ADHD-related differences in reading, whereas LNS alone explained ADHD-related differences in math. Collectively these findings suggest that strengthening deficient higher-level WM abilities, in conjunction with empirically based academic instruction, is needed to improve learning outcomes in children with ADHD.

Keywords Attention-deficit/hyperactivity disorder (ADHD) · Cognitive ability · FSIQ · WISC-IV · Working memory · Academic achievement

Attention-deficit/hyperactivity disorder (ADHD) is an early onset, neurodevelopmental disorder characterized by clinically impairing levels of inattention, hyperactivity, and impulsivity (American Psychological Association 2013). The disorder affects approximately 3.5 million children in the United States at an estimated annual cost of $38–72 billion (Doshi et al. 2012), a majority of which is associated with academic related difficulties experienced by children with ADHD.

Academic underachievement is a persistent problem for a majority of children with ADHD that begins as early as kindergarten and endures throughout adolescence (DuPaul et al. 2016; DuPaul and Stoner 2014). Compared to neurotypical peers, childhood ADHD is associated with poorer classroom productivity, lower grade point averages, higher rates of grade retention, lower scores on standardized academic achievement measures, and higher rates of school dropout (Barkley et al. 1990; Frazier et al. 2007; Loe and Feldman 2007; Scholtens et al. 2013). Comorbid learning disabilities in children with ADHD are common—particularly in reading (11% to 52%), math (5% to 30%), and writing (59% to 65%)—and a majority of children with ADHD experience academic deficits even in the absence of a comorbid specific learning disability (DuPaul et al. 2013; DuPaul et al. 2016). The presence of early academic difficulties in children with ADHD portend a range of adverse outcomes in late adolescence and early adulthood, including lower college matriculation and graduation rates (Weyandt and DuPaul 2013), lower levels of occupational attainment and employment, poorer job performance, and lower socioeconomic status (Erskine et al. 2016; Hechtman et al. 2016; Ramos-Olazagasti et al. 2018). Collectively, these findings underscore the need to elucidate the cognitive processes that underlie academic disadvantages among children with ADHD.

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Two oft-cited theoretical models proposed to account for the linkage between ADHD and academic achievement deficits are the core clinical symptom model and intellectual deficit model. A key hypothesis of the clinical model is that core ADHD symptoms—particularly inattentiveness—underlie academic achievement deficiencies by interfering with basic learning processes such as attending to, comprehending, and following classroom instructions (Breslau et al. 2009; Fergusson et al. 1997; Frick et al. 1991; Mash and Barkley 2003; Rabiner and Coie 2000). A logical extrapolation of the model's central premise is that treatment related remission of core symptoms (e.g., decreased inattentiveness) should translate into improved learning and academic achievement. Regrettably, multiyear clinical outcome studies fail to demonstrate this expected effect. For example, children assigned to the three primary treatment groups (individually titrated psychostimulant medication, comprehensive behavioral intervention, or combined treatment) of the Multimodal Treatment Study of Children with ADHD (MTA) exhibited significant improvement in all three core ADHD symptom domains (inattention, hyperactivity, impulsivity), but failed to improve significantly on any of the standardized educational achievement measures (DuPaul et al. 2016; Molina et al. 2009). Massetti and colleagues (Massetti et al. 2008) reported similar non-contributory effects of psychostimulant medication on children's academic achievement over an 8-year time frame. Collectively, findings derived from well-controlled outcome studies provide compelling evidence that improvement in ADHD symptoms do not correspond with improved academic achievement for a majority of children with ADHD, and indicates that other mechanisms and processes must be explored to inform the design of interventions that enhance learning related outcomes in this population.

An alternative model proposed to account for ADHD-related underachievement postulates intellectual functioning as a primary contributing factor. The intellectual deficit model is based on previous research demonstrating that (a) children with ADHD tend to have lower measured intelligence relative to typically developing peers (Crosbie and Schachar 2001; Frazier et al. 2004; Kuntsi et al. 2004; Mariani and Barkley 1997; Rucklidge and Tannock 2001); and (b) intelligence is strongly correlated with ($r = .87$; Wechsler 2003) and a causal antecedent to academic achievement (Watkins et al. 2007). Extant evidence also reveals that FSIQ predicts lower achievement for children regardless of diagnostic and socioeconomic status (McConaughy et al. 2011) or whether children receive pharmacological treatment and/or academic support (Corkum et al. 2010). FSIQ also predicts academic performance more accurately relative to parent ratings of ADHD and neuropsychological measures such as the Wisconsin Card Sorting Test, Stroop Color and Word Test, and California Verbal Learning Test (Mayes et al. 2009). In addition, a majority of empirical studies report that lower FSIQ scores among children with ADHD are not secondary to potentially disruptive test-taking behaviors such as inattentiveness and hyperactivity (Chae 1999; Holmes et al. 2009; Naglieri et al. 2005).

A derivative of the intellectual deficit model that may better explain the linkage between lower intellectual functioning and academic achievement in children with ADHD postulates that one or more specific areas of intellectual abilities conventionally measured by composite index scores—viz., Verbal Comprehension, Perceptual and Fluid Reasoning, Working Memory, and Processing Speed—rather than the influence of a general factor (g) deficiency (e.g., FSIQ) more accurately accounts for the relation with academic achievement. Partial support for the hypothesis is evidenced by studies reporting lower scores for children with ADHD relative to neurotypical peers on the older Freedom from Distractibility Index (FDI)[1] and three (Working Memory Index [WMI], Processing Speed [PSI], and Verbal Comprehension [VCI]) of the four WISC-IV composite indices (Anastopoulos et al. 1994; Andreou et al. 2005; Ek et al. 2013; Fenollar-Cortés et al. 2015; Mayes and Calhoun 2006, 2007; McConaughy et al. 2009).

Only two studies to date have examined whether multiple areas of specific intellectual abilities are related to academic achievement deficits in children with ADHD. The first of these reported that WMI and VCI of the WISC-IV were the strongest predictors of standardized academic achievement scores in children and adolescents with ADHD (Mayes and Calhoun 2007), a finding consistent with those reported for children with learning disabilities (Hale et al. 2001) and neurotypical children (Konold et al. 1999). A second, more recent study reported similar findings wherein children and adolescents with ADHD who scored lower on PSI and combined WMI/PSI composite indices exhibited significant impairment in reading and math (Thaler et al. 2012).

Despite the notable contributions of the two studies in explicating the relations between specific intellectual abilities and achievement in ADHD, neither included a neurotypical (NT) community control group, and both included a relatively high proportion of children diagnosed with ADHD-predominantly inattentive presentation (32% and 56%, respectively). Consequently, it remains unknown whether the specific areas of intellectual ability identified in the two studies serve as significant mediators of achievement differences between children with ADHD and NT children, and whether processing speed's negative relation with academic performance is unique to the ADHD-predominantly inattentive presentation as evidenced in past studies (Goth-Owens et al. 2010; Solanto et al. 2007; Weiler et al. 2000) or extends to the more commonly diagnosed ADHD-combined presentation. Elucidating the intellectual predictors of academic

[1] The FDI, which included an arithmetic subtest, was discontinued in the WISC-IV and replaced with the Working Memory Index (WMI) to eliminate the potentially biasing effect of arithmetic knowledge on FSIQ.

underachievement among children with ADHD-combined presentation is necessary because (a) extant literature indicates varied neurocognitive profiles among ADHD subtypes (cf. Willcutt et al. 2005, for a meta-analytic review), (b) the majority of school-aged children with the disorder are diagnosed with the combined presentation, and (c) mediational influences of academic achievement may differ for the different presentation subtypes. Identifying specific areas of cognitive weaknesses is also needed because some (e.g., verbal abilities; Kennedy et al. 2013) are more malleable to training and development than are others (e.g., non-verbal abilities; Chooi and Thompson 2012; Harrison et al. 2013). Finally, the WM/academic achievement relation documented in the two studies discussed above is notable; however, knowing whether the relation reflects the combined influences of the upper level central executive (CE) and lower level short-term *memory* (STM) components or STM alone[2] warrants scrutiny given past evidence that verbal STM is significantly more amenable to training than are upper level central executive processes (Melby-Lervag and Hulme 2013; Rapport et al. 2013).

For purposes of the present study, verbal comprehension (VCI) and working memory (WMI) scores of the WISC-IV were hypothesized to significantly mediate ADHD-related academic achievement deficits, as verbal IQ shows stronger relations with achievement relative to performance IQ (Kauffman and Kauffman 2004; Psychological Corporation 2002; Wechsler 2003, 2014) and extant literature corroborates working memory's involvement in children's learning and achievement (Alloway and Alloway 2010; Swanson and Alloway 2012). Neither perceptual reasoning (PRI) nor processing speed (PSI) abilities was expected to serve as a significant mediator of ADHD-related achievement deficits. Empirical investigations reveal non-significant ADHD/NT differences in PRI scores (Fenollar-Cortés et al. 2015), and recent investigations examining neuropsychological differences in children with ADHD-combined presentation relative to ADHD-predominantly inattentive presentation consistently report that processing speed deficits are unique to the latter subtype (Goth-Owens et al. 2010; Mayes et al. 2008). A secondary analysis was also planned to determine whether one or both WMI subtests (Letter-Number Sequencing, Digit Span) account for the expected WMI mediation effect of ADHD-related academic achievement difficulties. The Letter-Number Sequencing (LNS) subtest alone was hypothesized to serve as a significant mediator because it requires both domain general CE processes as well as STM (Rapport et al. 2008a) and its relation with academic achievement is well established (Swanson and Alloway 2012). WISC-IV Digit Span, in contrast, measures verbal STM and appears minimally impaired in ADHD (Kasper et al. 2012; Tarle et al. 2017; Wells et al. 2018).

[2] The *working* component of WM (i.e., the central executive [CE]) is considered a domain general attentional controller that involves multiple executive processes (e.g., updating, manipulation/dual processing, serial reordering, interference control) responsible for the mental processing of information held temporarily in the phonological and visuospatial short-term memory stores (Baddeley 2012).

Methods

Participants

The sample comprised 54 boys aged 8 to 12 years ($M = 9.76$, $SD = 1.29$) recruited by or referred to a university-based 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 38 Caucasian Non-Hispanic (70%), 9 Hispanic English speaking (17%), 4 bi- or multi-racial (7%) and 3 African American (6%) 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 ($n = 28$), and neurotypical boys ($n = 26$) 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-5 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).

Twenty-eight boys meeting all of the following criteria were included in the ADHD-combined presentation group: (1) an independent diagnosis by the directing clinical psychologist using DSM-5 criteria for ADHD-combined presentation 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). Two of the children (7.14%) also met diagnostic criteria for Oppositional Defiant Disorder (ODD).

Twenty-six boys met the following criteria and were included in the neurotypical group (NT): (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 the CSI ADHD-combined subscale.

Procedures

The Wechsler Intelligence Scale for Children 4th edition (WISC-IV; Wechsler 2003) and the Kaufman Test of Educational Achievement 1st or 2nd edition (KTEA-I-Normative Update; Kaufman and Kaufman 1998; KTEA-II; Kaufman and Kaufman 2004) were administered to each child during two separate weekday testing sessions one week apart to minimize fatigue. The changeover to KTEA-II was due to its release during the study and to provide parents the most up-to-date educational evaluation possible. All psychoeducational assessments were conducted over a 6-year time period and represent consecutive referrals to the clinic through early 2018.

Measures

Intellectual Abilities The WISC–IV provides an overall measure of intellectual functioning, the Full Scale Score (FSIQ), as well as composite indices relating to four specific cognitive abilities: Verbal Comprehension Index (VCI), Perceptual Reasoning Index (PRI), Working Memory Index (WMI), and Processing Speed Index (PSI). VCI subtests (Similarities, Vocabulary, Comprehension) measure verbal reasoning, conceptualization, expression and stored knowledge, whereas PRI subtests (Block Design, Picture Concepts, Matrix Reasoning) measure fluid reasoning in the perceptual domain with tasks that assess nonverbal concept formation. WMI subtests measure the ability to temporarily store (Digit Span), sequence, and mentally manipulate (Letter-Number Sequencing) phonological information; and PSI subtests (Coding, Symbol Search) measure concentration, visual-motor coordination, visual discrimination, and the ability to process visually perceived information efficiently. Children were administered all WISC-IV subtests following standardized manual instructions by trained doctoral students under the supervision of a licensed clinical psychologist. Standardized scores for the four composite indices (VCI, PRI, WMI, PSI) as well as WM subtests (Digit Span, Letter-Number Sequencing) were calculated and used to evaluate study hypotheses.

Academic Achievement Age-corrected, standardized Reading and Math Composite scores from the KTEA-I-NU (Kaufman and Kaufman 1998) or KTEA-II (Kaufman and Kaufman 2004) served as the dependent variables to assess academic achievement ($r = 0.77$ between the two versions; Kaufman and Kaufman 2004). Reading and Math Composite scores were fixed to one factor via principle components factor analysis (factor loadings were .84 and .84 for Reading and Math, respectively) to provide an overall estimate of Academic Achievement. The Reading Composite score is comprised of scores from the Decoding (KTEA-I) or the Letter & Word Recognition subtest (KTEA II), which assess children's ability to identify letters and words of gradually increasing difficulty ($r = 0.84$ between the two subtests; Kaufman and Kaufman 2004), and the Reading Comprehension subtest (KTEA-I or -II), which assesses knowledge of literal and inferential meaning of reading passages. The Math Composite score is comprised of scores from the Mathematics Applications (KTEA-I) or the Mathematics Concepts & Applications (KTEA-II) subtests ($r = 0.83$ between the two versions, Kaufman and Kaufman 2004), which assesses knowledge of arithmetic concepts and reasoning skills, and the Mathematics Computation subtest (KTEA-I or -II), which assesses knowledge of arithmetic operations.

Data Analysis Independent t-tests were used to investigate between-group (ADHD, NT) differences in WISC-IV composite indices (i.e., VCI, PRI, WMI, PSI). Statistical regression analysis using maximum likelihood was used subsequently to examine the extent to which significant between-group WISC-IV composite indices mediate the relationship between Diagnostic Status (ADHD, NT) and Academic Achievement. Analyses were completed using bias-corrected bootstrapping to minimize Type II error as recommended by Shrout and Bolger (2002), and 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 (Hayes 2014) was used for all analyses and 10,000 samples were derived from the original sample ($n = 54$) by a process of resampling with replacement (Hayes 2013; Shrout and

Bolger 2002). Effect ratios (ER; 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, and indirect effects were also calculated.

Results

Preliminary Analysis

All independent and dependent variables were screened for univariate outliers to identify scores exceeding 3.0 standard deviations from the mean in either direction (Tabachnick and Fidell 2007). No outliers were found.

Independent T-Tests and Zero-Order Correlations

The ADHD and NT groups did not differ on age (p =.205) or SES (p =.321), the latter of which was derived using the Hollingshead Four Factor Index of Social Status (Hollingshead 1975). As expected, parent and teacher behavior rating scale scores were significantly higher and KTEA Academic Achievement scores were significantly lower for the ADHD relative to the NT group (Table 1). FSIQ scores were also significantly lower for the ADHD relative to the NT group ($p \le 0.05$) and reflected lower scores on two (VCI: Verbal Comprehensive Index; WMI: Working Memory Index; both p-values ≤0.05) of the four WISC-IV indices as depicted in Table 1. FSIQ was not used as a covariate due to the experimental design of the investigation (i.e., planned analyses were used to examine mediators of any significant between-group differences in the four factor indices as described below). As a result, mediation model results with no covariates are reported below.

Zero-order correlations between Diagnostic Status, WISC-IV index scores, and the Academic Achievement factor score were computed. Diagnostic Status and the WISC-IV four index scores were correlated significantly with Academic Achievement; however, Diagnostic Status was correlated significantly with only two (WMI, VCI) of the four WISC-IV index scores (see Table 2), and both were included in the models described below based on a priori hypotheses that reflect extant literature.[3]

Power Analysis

A large magnitude effect size was predicted based on established relations between ADHD and WM abilities (d = 1.41–2.31, Kofler et al. 2018; Rapport et al. 2008a, 2008b), between ADHD and VCI (d = 0.71; Andreou et al. 2005), between WMI and academic achievement (r = .66 to.79; Kaufman and Kaufman 2004; Parkin and Beaujean 2012; Wechsler 2003), and VCI and academic achievement (r = .79 to .80; Kaufman and Kaufman 2004; Wechsler 2003). As noted by Preacher and Hayes (2008), few studies have examined power for multiple mediators, and to our knowledge, there are no currently available tools for computing mediation power for the parallel mediation models used in the current study. Based on the available evidence, however, there is reason to suggest that we are adequately powered for bias-corrected, bootstrapped tests of two mediators with our n = 54. Specifically, Briggs (2006) reported a series of simulations to estimate power for parallel models with two mediators. Conservatively assuming partial rather than full mediation, and approximately equal contributions of each mediator, n = 50 produced power = .90–.92. The current sample size of 54 exceeds this minimum criterion.

Mediation Effects of WMI and VCI on ADHD-Related Academic Achievement Deficits

A two-tier data analytic approach using parallel mediation models was followed to address the study's central hypotheses. A defining feature of the parallel multiple mediation model is the constraint that each potential mediator is modeled controlling for (holding constant) all other mediators in the model to allow competing hypotheses of mechanisms or processes to be examined independently of one another (Hayes 2018).

Tier 1: Unique Contributions of WMI and VCI

A parallel mediation model using the PROCESS script for SPSS (Hayes 2013) was tested to determine the extent to which WMI and VCI uniquely account for between-group differences in Academic Achievement. Examination of the total effect revealed that Diagnostic Status (ADHD, NT) was related significantly to Academic Achievement (d = −0.96), such that boys with ADHD demonstrated large magnitude Academic Achievement deficits prior to accounting for the potential mediating roles of VCI- and WMI-related processes. The total effect of Diagnostic Status on Academic Achievement was attenuated significantly when WMI and VCI were included as mediators (d = −0.49; 95% CI [−0.87, −0.10]; see Fig. 1, Direct Effect), such that their combined effects accounted for 50% of the ADHD/Academic Achievement relation (ER = .50; d = −0.47; 95% CI [−0.85, −0.16]; see Fig. 1, Total Indirect Effect). This combined effect was carried to a somewhat greater extent by the mediating role of WMI, which accounted for 30% of the Diagnostic Status/Academic Achievement relation (ER = .30; d = −0.29; 95% CI [−0.65, −0.04]; see Fig. 1, Indirect Effect 1) independent of the influence of VCI. In contrast, the contribution of VCI independent of WMI (20%) was somewhat smaller (ER = .20; d = −0.18; 95% CI [−0.42, −0.04]; see Fig. 1, Indirect Effect 2).

[3] A posteriori analyses including PRI and PSI as potential mediators confirmed that neither included significant indirect effects.

Table 1 Sample demographics

Variable	ADHD		NT		
	$\bar{x}$	*SD*	$\bar{x}$	*SD*	*t*
Age	9.54	1.26	9.99	1.31	1.28
FSIQ	105.21	10.33	110.81	9.18	2.10*
SES	51.04	8.62	53.65	10.53	1.00
CBCL AD/HD Problems	72.14	6.43	51.85	4.87	12.87*
TRF AD/HD Problems	68.28	7.65	52.04	4.39	9.18*
CSI-P: ADHD, Combined	76.11	8.95	46.15	9.79	11.74*
CSI-T ADHD, Combined	69.57	9.20	45.67	5.01	11.35*
VCI	108.10	10.02	114.42	10.51	2.26*
PRI	106.61	13.10	109.31	10.55	0.83
WMI	100.64	10.43	107.50	11.47	2.30*
PSI	96.64	10.73	97.54	12.54	.28
KTEA Reading Scaled Score	105.39	11.50	116.39	11.92	3.99*
KTEA Math Scaled Score	101.68	14.00	112.50	14.01	3.45*
Academic Achievement Factor	−.46	.84	.49	.93	2.98*

ADHD attention-deficit/hyperactivity disorder, *NT* Neurotypical, *FSIQ* Full Scale Intelligence Quotient, *SES* socioeconomic status, *CBCL* Child Behavior Checklist DSM- Oriented Scales raw scores, *TRF* Teacher Report Form DSM-Oriented Scales raw scores, *CSI* Child Symptom Inventory severity raw scores, *VCI* WISC-IV Verbal Comprehension Index Score, *PRI* WISC-IV Perceptual Reasoning Index Score, *WMI* WISC-IV Working Memory Index Score, *PSI* WISC-IV Processing Speed Index Score, *KTEA* Kaufmann Test of Educational Achievement

*$p \leq 0.05$

Collectively, these findings indicate that a substantial portion of academic achievement deficiencies observed among children with ADHD relative to TD children is explained by underdeveloped working memory and verbal comprehension intellectual abilities.

Tier 2: Unique Contributions of Working Memory Index Components

A second parallel model was used to determine whether the cognitive processes associated with the two WMI subtests (Digit Span, Letter-Number Sequencing) that comprise the WMI used in the preceding model contribute uniquely to ADHD-related Academic Achievement deficiencies or reflect an epiphenomenon effect.[4] Digit Span (DS) measures temporary maintenance (storage) of verbal information, whereas Letter-Number Sequencing (LNS) measures both short-term storage and manipulation of phonological information (Engle et al. 1999; Oberauer et al. 2000).

Results of the parallel model revealed that LNS (ER = .23; *d* = −0.21, 95% CI [−0.54, −0.04]) but not DS (95% CI includes 0.0) explained unique variance in the ADHD/Academic Achievement relation as depicted in Fig. 2. This finding indicates that the unique contribution of working memory to ADHD-related Academic Achievement difficulties revealed in the preceding parallel model reflects the combined contribution of upper level CE and lower level short-term memory storage processes, rather than lower level short-term memory storage alone.[5]

Substituting LNS for WMI in the parallel model involving VCI resulted in nearly identical findings as reported in the previous WMI/VCI parallel model. LNS and VCI uniquely (ER = .26 and .22, respectively) and jointly (ER = .47) accounted for 47% of the ADHD/Academic Achievement relation.

Auxiliary Analyses

Two post-hoc parallel mediation models were constructed to evaluate the possibility that the mediating effect of VCI on ADHD-related Academic Achievement (comprised of KTEA Reading and Math Composite scores) reported above might have occurred solely due to the association between VCI and Reading. Results revealed that both LNS (ER = .26; *d* = −0.21, 95% CI [−0.54, −0.04]) and VCI (ER = .26; *d* = −0.21, 95% CI [−0.54, −0.04]) contributed uniquely and nearly identically to ADHD-related Reading Abilities. In contrast,

[4] Epiphenomena effects reflect a situation in which two variables are correlated and significant mediators when modeled separately, but only one is a true mediator of the relation and the other a correlated process that arises from but does not causally influence the process; cf. Hayes 2018, for an expanded discussion.

[5] Neither Digit Span Forward nor Digit Span Backward served as significant mediators of the ADHD-Academic Achievement relation when examined separately.

Table 2 Zero Order Correlations Between WISC-IV Index Scores and Academic Achievement

		1	2	3	4	5
1	Diagnostic Status (NT = 0, ADHD = 1)					
2	VCI	−.30*				
3	PRI	−.11	.35*			
4	WMI	−.30*	.32*	.46*		
5	PSI	−.04	.09	.29*	.30*	
6	Academic Achievement Factor	−.48*	.54*	.41*	.65*	.27*

ADHD attention-deficit/hyperactivity disorder, *NT* Neurotypical, *VCI* WISC-IV Verbal Comprehension Index Score, *PRI* WISC-IV Perceptual Reasoning Index Score, *WMI* WISC-IV Working Memory Index Score, *PSI* WISC-IV Processing Speed Index Score

*$p \leq 0.05$

LNS (ER = .26; d = −0.19, 95% CI [−0.54, −0.01]) but not VCI (95% CI includes 0.0) contributed to ADHD-related Math abilities. Results are depicted in Fig. 3.

Collectively, the Tier 1, Tier 2, and post-hoc analyses indicate that ADHD-related deficits in Reading reflect deficiencies in both WM processes and crystallized, verbal intellectual abilities, whereas ADHD-related deficits in Math reflect deficiencies in WM processes.

Discussion

The co-occurrence of lower full-scale intellectual abilities (FSIQ) and academic achievement deficits in children with ADHD is well established (Crosbie and Schachar 2001; Frazier et al. 2004; Kuntsi et al. 2004; Mariani and Barkley 1997; Rucklidge and Tannock 2001); however, the extent to which the relation reflects the influence of a general factor (g) deficiency or deficiencies in one or more specific intellectual abilities remains speculative and was the focus of the current study. Establishing this relation is warranted in light of empirical evidence demonstrating that (a) intellectual abilities are an antecedent of and contribute significantly to children's academic achievement (Watkins et al. 2007); (b) specific intellectual abilities exhibit differential relations with foundational learning (Alloway and Alloway 2010; Gathercole et al. 2006; Swanson and Alloway 2012); and (c) early intellectual abilities are the only significant predictor of multiple

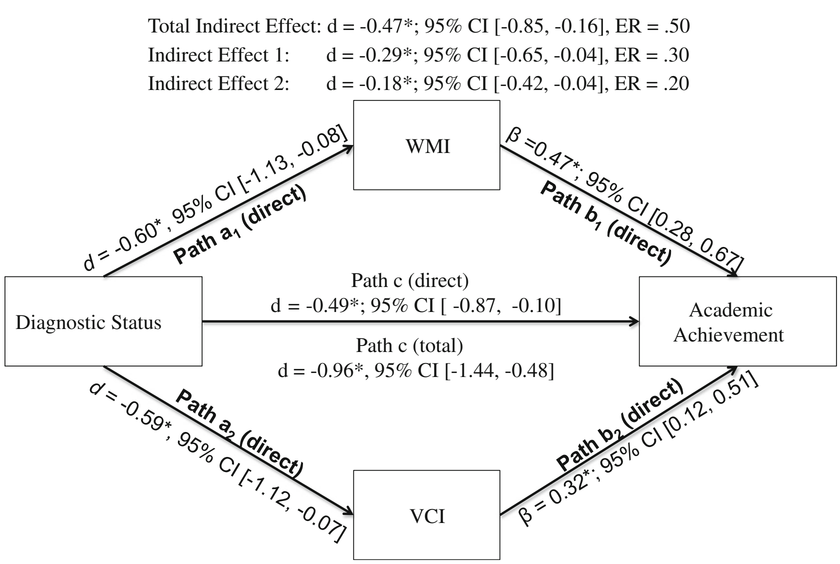

Fig. 1 **Unique Contributions of WMI and VCI.** Schematic depicting the effect sizes, and β coefficients of the total, direct, and indirect pathways for serial mediation of the Working Memory Index (WMI) and Verbal Comprehensive Index (VCI) on the relation between Diagnostic Status and Academic Achievement. Cohen's d for the c and c' pathways reflects the impact of ADHD diagnostic status on Academic Achievement before (path c) and after (path c') taking into account the mediating variables. *Effect size (or β-weight) is significant based on 95% confidence intervals that do not include 0.0 (Shrout and Bolger 2002); values for path b reflect β- weights due to the use of two continuous variables in the calculation of the direct effect. Indirect Effect 1 represents the mediating effect of WMI independent of VCI on Academic Achievement. Indirect Effect 2 represents the mediating effect of VCI independent of the WMI on Academic Achievement. Total Indirect Effect represents the collective influence of both mediation pathways. CI = confidence interval

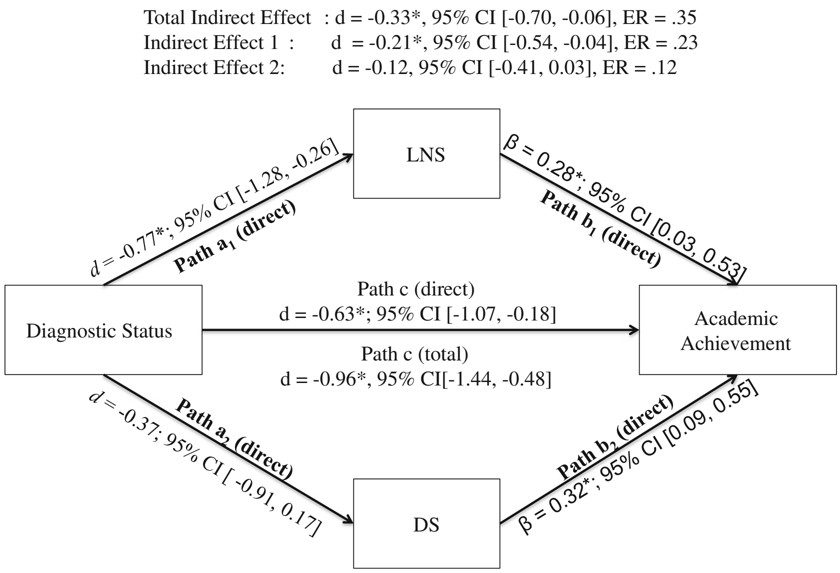

Fig. 2 **Unique Contributions of Working Memory Index Subtests.** Schematic depicting the effect sizes, and β coefficients of the total, direct, and indirect pathways for serial mediation of Letter Number Sequencing (LNS) and Digit Span (DS) on the relation between Diagnostic Status and Academic Achievement. Cohen's d for the c and c' pathways reflects the impact of ADHD diagnostic status on Academic Achievement before (path c) and after (path c') taking into account the mediating variables. *Effect size (or β-weight) is significant based on 95% confidence intervals that do not include 0.0 (Shrout and Bolger 2002); values for path b reflect β- weights due to the use of two continuous variables in the calculation of the direct effect. Indirect Effect 1 represents the mediating effect of LNS independent of DS on Academic Achievement. Indirect Effect 2 represents the mediating effect of DS independent of the LNS on Academic Achievement. Total Indirect Effect represents the collective influence of both mediation pathways. CI = confidence interval

outcomes in adult ADHD such as educational achievement, occupational rank, and occupational adjustment (Ramos-Olazagasti et al. 2018).

The study focused exclusively on boys with and without ADHD due to the well-documented gender differences in ADHD-related neurocognitive functioning (Balint et al. 2009) and neural morphology (Dirlikov et al. 2015; Wang et al. 2018), and greater intellectual impairment (Gaub and Carlson 1997) and symptom presentation/severity (Gershon and Gershon 2002; Williamson and Johnston 2015) reported for girls with ADHD.

Consistent with past investigations (Crosbie and Schachar 2001; Frazier et al. 2004; Kuntsi et al. 2004; Mariani and Barkley 1997; Rucklidge and Tannock 2001) and intellectual deficit model hypotheses, our results revealed that FSIQ was significantly lower in children with ADHD relative to neurotypical (NT) community control children. Examination of the four WISC-IV index scores, however, revealed that the group level difference in FSIQ resulted from lower scores on two of the four specific intellectual ability indices—viz., Working Memory (WMI) and Verbal Comprehension (VCI)—corroborating previous findings of lower WMI and VCI scores in children with ADHD (Anastopoulos et al. 1994; Andreou et al. 2005; Ek et al. 2013; Fenollar-Cortés et al. 2015; Mayes and Calhoun 2006, 2007).

The non-significant between-group differences in Perceptual Reasoning (PRI) and Processing Speed (PSI) abilities were also consistent with a priori hypotheses, congruent with studies reporting unimpaired perceptual reasoning abilities (Fenollar-Cortés et al. 2015; Wechsler 2003, 2014), but discordant with investigations reporting impaired processing speed in children with ADHD (Frazier et al. 2004; Mayes and Calhoun 2006, 2007). The most cogent explanation for the discrepant PSI results is that previous investigations reporting impaired processing speed included high percentages of children with ADHD-predominantly inattentive presentation (ADHD-I), whereas the present study excluded these children intentionally based on a growing consensus that slowed processing speed may be unique to ADHD-I (Calhoun and Mayes 2005; Chhabildas et al. 2001; Goth-Owens et al. 2010; Mayes et al. 2008; Thaler et al. 2012).

A parallel mediation model was used to determine whether memory and crystalized intelligence explained unique variance in ADHD-related academic achievement or represent an epiphenomenon effect (i.e., a correlated set of abilities that arises from but does not causally influence the relation). Results revealed that, although both abilities jointly accounted for 50% of the variance in ADHD-related academic deficits, working memory and crystalized verbal knowledge each uniquely contributed to the relation. This finding is consistent with previous investigations reporting a robust influence of working memory and verbal comprehension abilities on academic achievement in children with ADHD (Mayes and Calhoun 2007), and extends those findings by contrasting the results with a NT community control group. The findings are also analogous to those

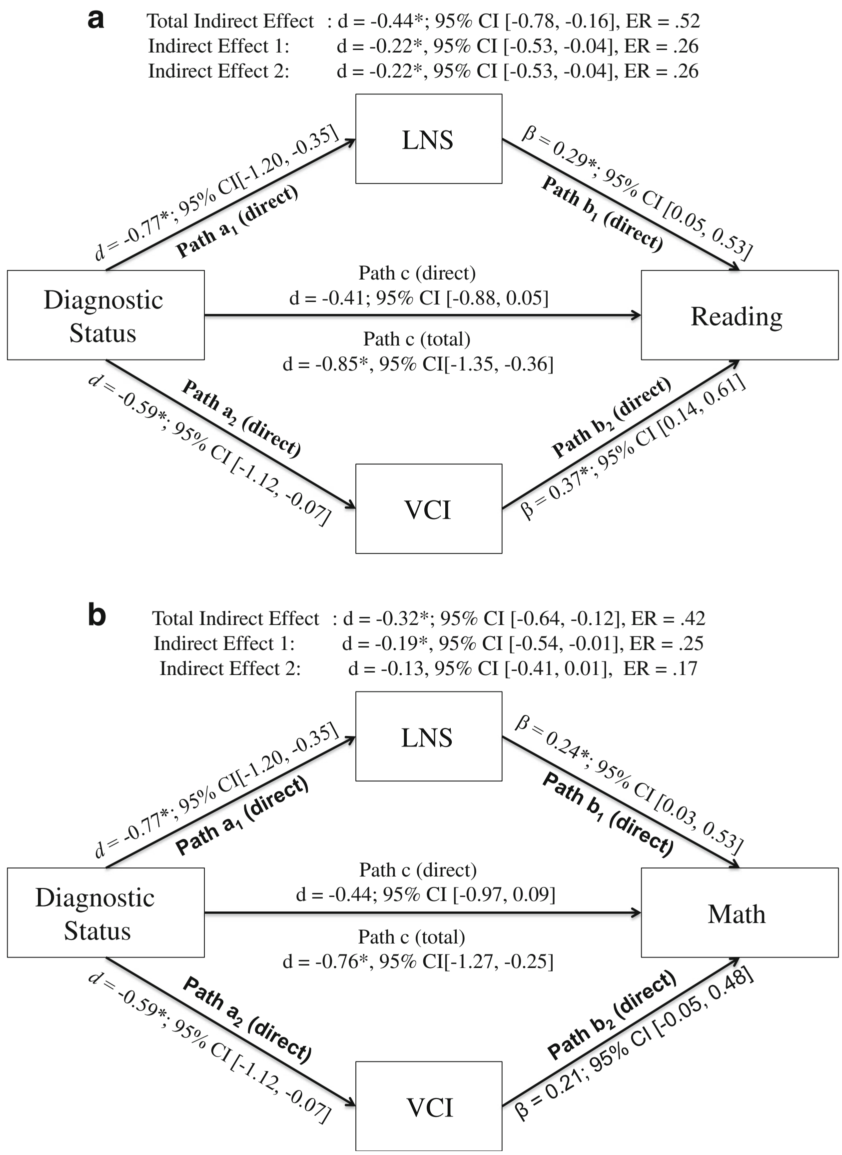

Fig. 3 **Auxiliary Analyses.** Schematic depicting the effect sizes, and β coefficients of the total, direct, and indirect pathways for serial mediation of Letter Number Sequencing (LNS) and the Verbal Comprehensive Index (VCI) on the relation between Diagnostic Status and a) KTEA Reading Composite scores and b) KTEA Math Composite scores. Both LNS and VCI contributed uniquely to ADHD-related reading abilities, whereas LNS alone contributed uniquely to ADHD-related math abilities. Indirect Effect 1 for Fig. 3a and b are designated as a_1b_1 paths; Indirect Effect 2 for Fig. 3a and b are designated as a_2b_2 paths. *CI* confidence interval. *KTEA* Kaufmann Test of Educational Achievement. *Effect size (or β-weight) is significant based on 95% confidence intervals that do not include 0.0 (Shrout and Bolger 2002); values for path b reflect β- weights due to the use of two continuous variables in the calculation of the direct effect

reported in previous studies in which semantic language and WM were found to mediate the association between ADHD symptoms and reading and math standardized test scores (Gremillion and Martel 2012). Our planned *post-hoc* analyses, however, revealed that WM's contribution to children's academic achievement reflected deficient domain general, upper level central executive processes working in concert with lower level short-term memory (Letter-Number Sequencing), whereas verbal short-term memory alone (Digit Span) was not a significant mediator. This finding is consistent with previous investigations dissociating central executive from short-term memory (STM) processes when examining WM's contribution to academic functioning in children with ADHD (Kofler et al. 2018), and with studies indicating that verbal STM is minimally impaired in ADHD (Kasper et al. 2012; Martinussen et al. 2005; Tarle et al. 2017; Wells et al. 2018).

A posteriori parallel mediation models were used to determine whether the WM (Letter-Number Sequencing) and VCI meditational effects on overall achievement were due to verbal comprehension's expected robust relation with reading, but not math. As suspected, verbal comprehension abilities were related exclusively to children's reading achievement, whereas WM (Letter-Number Sequencing) was a significant mediator of reading and math achievement. The latter finding is consistent with a burgeoning literature documenting the involvement of phonological WM processes in reading (Gathercole et al. 2006; Gremillion and Martel 2012; Kofler et al. 2018; Rogers et al. 2011; Titz and Karbach 2014), math (Swanson and Alloway 2012; Swanson and Fung 2016; Titz and Karbach 2014), and written expression (Rodríguez et al. 2017), as well as a wide array of academic-related activities such as complex learning (Swanson and Kim 2007) and lexical-semantic abilities (Lui and Tannock 2007).

Theoretical perspectives regarding the processes by which WM influences reading and math in children with ADHD suggest several possibilities. One is that default mode network dysfunction diminishes focused attention while engaged in core academic areas such as reading and math (e.g., Fassbender et al. 2009); however, previous studies examining the interplay between attention and WM ability indicate that higher-order CE deficiencies remain after accounting for attention deficits in children with ADHD (Kofler et al. 2010). A second possibility is that underdeveloped CE-related interference control allows irrelevant internal and/or external information to gain access to and interfere with reading and math information held temporarily in PH STM (Swanson and Fung 2016); however, the lack of PH STM (Digit Span) involvement alone in ADHD-related academic achievement deficits renders this explanation unlikely. A more parsimonious explanation of the significant interplay between CE and academic achievement deficits in ADHD is that they reflect multiple CE processes that impact the retrieval, updating, and manipulation of academic information from long-term memory that enable knowledge to be readily connected with task performance. The unique and synergistic contributions of these processes, in turn, likely places additional demands on available CE resources and limits their availability for extracting knowledge while engaged in reading and math activities (Perfetti et al. 2007; Swanson and Alloway 2012). The current study, however, did not fractionate the distinct CE related processes to elucidate their unique and/or interactive contributions to ADHD-related reading and math difficulties, but such distinctions warrant investigation.

Despite methodological refinements (e.g., inclusion of a control group, bootstrapped mediation techniques to control for epiphenomenon effects) and the use of a well-characterized sample of children with and without ADHD, several limitations warrant consideration. By design, we cannot determine whether findings generalize to females or children diagnosed with ADHD-I. Future studies may benefit from investigating potentially moderating influences of gender and ADHD presentation type. The inclusion of larger and more diverse samples of children with other clinical disorders (e.g., Autistic Spectrum Disorder) and specific learning disabilities in which working memory and verbal comprehension deficits are suspected also warrant scrutiny. Although the sample size of the current study exceeded recommended guidelines for detecting the expected magnitude of effects for the study design (Fritz & 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. Additional investigation is also warranted to examine the extent to which the current results extend to children with lower estimated FSIQ. Finally, we also acknowledge that mediation analysis assumes a temporal ordering of the mediating and dependent constructs and that causality cannot be substantiated. The temporal sequencing adopted in the current study, however, was based on extant research that provides compelling evidence regarding the developmental sequence of intelligence and achievement in children (Watkins et al. 2007).

The present study revealed that WM and verbal comprehension abilities significantly mediate ADHD related academic achievement deficits, and have potential implications for the implementation of school-based interventions for children with ADHD. Gold standard pharmacological and psychological interventions ameliorate ADHD core clinical symptoms to a significant extent, but have minimal or no effect on academic outcomes (DuPaul et al. 2016; Molina et al. 2009). The current study's findings suggest that strengthening deficient executive functions such as WM, in conjunction with empirically based academic instruction, is needed to improve learning outcomes in children with ADHD. Complementary fMRI/fNIRS neuroimaging and functional connectivity studies are also warranted to elucidate the neural networks implicated in ADHD-related academic achievement difficulties. Collectively, this information can be used to inform the design/development of reading and math interventions for children with ADHD and to determine whether changes in targeted neural networks are associated with improved academic functioning.

Compliance with Ethical Standards

Conflict of Interest Catrina A. Calub, Mark D. Rapport, Lauren M. Friedman, and Samuel J. Eckrich declare that they have no conflict of interest.

Experiment Participants 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.

Ethical Approval Institutional Review Board (IRB) approved use of this information for research purposes.

Informed Consent Informed consent and assent was obtained from all parents/legal guardians and children participating in the study, respectively.

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