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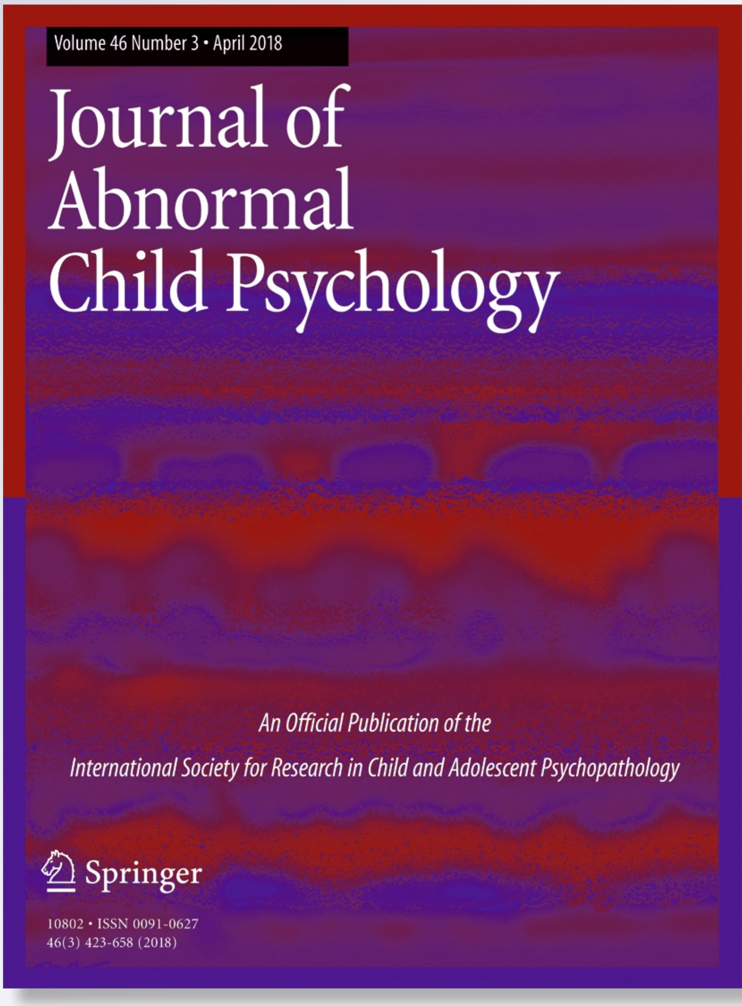

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Applied Problem Solving in Children with ADHD: The Mediating Roles of Working Memory and Mathematical Calculation

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

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Abstract The difficulties children with ADHD experience solving applied math problems are well documented; however, the independent and/or interactive contributions of cognitive processes underlying these difficulties are not fully understood and warrant scrutiny. The current study examines two primary cognitive processes integral to children's ability to solve applied math problems: working memory (WM) and math calculation skills (i.e., the ability to utilize specific facts, skills, or processes related to basic math operations stored in long-term memory). Thirty-six boys with ADHD-combined presentation and 33 typically developing (TD) boys aged 8–12 years old were administered multiple counterbalanced tasks to assess upper (central executive [CE]) and lower level (phonological [PH STM] and visuospatial [VS STM] short-term memory) WM processes, and standardized measures of mathematical abilities. Bias-corrected, bootstrapped mediation analyses revealed that CE ability fully mediated between-group differences in applied problem solving whereas math calculation ability partially mediated the relation. Neither PH STM nor VS STM was a significant mediator. When modeled together via serial mediation analysis, CE in tandem with math calculation ability fully mediated the relation, explained 79% of the variance, and provided a more parsimonious explication of applied mathematical problem solving differences among children with ADHD. Results suggest that interventions designed to address applied math difficulties in children with ADHD will likely benefit from targeting basic knowledge of math facts and skills while simultaneously promoting the active interplay of these skills with CE processes.

Keywords Attention/deficit-hyperactivity disorder (ADHD) · Working memory · Mathematics · Arithmetic calculation · Applied math problems, executive functions

Attention-deficit/hyperactivity disorder (ADHD) is an early onset, neurodevelopmental disorder characterized by clinically impairing levels of inattention, hyperactivity, and impulsivity that affects an estimated 5% of school-aged children (American Psychiatric Association 2013). The disorder is associated with numerous learning difficulties across the broad academic areas including reading, writing, spelling, and math (DuPaul et al. 2013; Frazier et al. 2007). Children with ADHD appear to be particularly susceptible to math-related difficulties as evidenced by increased rates of Specific Learning Disorder in Mathematics (20% comorbidity rates; DuPaul et al. 2013), lower scores on standardized mathematics tests ($d = 0.67$; Frazier et al. 2007), poorer grades in math (Daley and Birchwood 2010; Titz and Karbach 2014), and decreased productivity during math-related classroom activities (Rapport et al. 2009a; b; Vile Junod et al. 2006). Math deficits in early education are of particular concern given that foundational mathematical knowledge is a requisite and critically important precursor for learning advanced mathematical concepts introduced in contemporary middle and high school curricula such as algebra, geometry, and pre-calculus. Early math difficulties also portend multiple adverse outcomes including later math difficulties (Judge and Watson 2011), delinquent behavior (Maguin and Loeber 1996), and lower high school and college graduation rates (National Longitudinal Transition Study 2 2009), occupational skills (Mathews et al.

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1982), and socioeconomic status in adulthood (Ritchie and Bates 2013).

Two primary cognitive processes have been implicated in attempts to explicate applied mathematical problem-solving difficulties in children with ADHD—viz., working memory (WM) and mathematical calculation performance skills (see Zentall and Ferkis 1993, for a review). WM is a multi-component system responsible for the temporary storage, rehearsal, maintenance, processing, updating, and manipulation of internally held information (Baddeley 2007). The domain general working component consists of a central executive (CE) supervisory system that controls attentional focus, minimizes interference effects (i.e., inhibits irrelevant internal/external information from competing with information held or processed in memory), reacts to multi-task demands, and oversees/coordinates two modality specific memory subsystems (i.e., phonological short-term memory [PH STM] and visuospatial short-term memory [VS STM]) that upload information from long-term memory.

Solving applied mathematical problems requires multiple interacting WM processes to comprehend and represent real-world scenarios in the correct mathematical form (e.g., interpreting graphs, exchanging money; Swanson and Fung 2016; Swanson and Jerman 2006). The two STM subsystems have distinct albeit complementary roles for handling modality specific information and processing applied math problems. The PH STM subsystem temporarily preserves verbal information contained in the mathematical word problem (e.g., numbers/mathematical rules stored in long-term memory) and partial solutions calculated for a sufficient duration to solve complex word problems (Heathcote 1994; Swanson and Fung 2016; Swanson and Sachse-Lee 2001). In a complementary fashion, the VS STM subsystem temporarily stores nonverbal representations such as math-related visual imagery used to support mental calculation activities, maintains relevant spatial relations temporarily, and organizes visual information (e.g., lining up the tens place correctly) during mathematical calculations (Simmons et al. 2012). Coordination within and between the two STM subsystems is superintended by the domain general CE to (a) determine the task-relevance of the information contained in the mathematical word problem; (b) update information in PH/VS STM with newer, more relevant information; (c) connect information contained in the mathematical word problem with knowledge stored in long-term memory regarding math rules and potential mathematical algorithms to be applied in the current problem; (d) maintain the overall goal of the applied problem; and (e) sustain attentional focus while concomitantly inhibiting irrelevant information from entering/competing with temporarily stored information (Simmons et al. 2012; Swanson and Fung 2016). For purposes of understanding children's applied mathematics difficulties, deficiencies in either the PH STM or VS STM subsystem may hinder CE-mediated cognitive processing by creating a potential bottleneck and constricting the flow of information upward towards the CE and diverting CE resources to compensate for deficient storage and/or covert maintenance abilities. Alternatively, underdeveloped CE processes can limit the active updating, processing, and coordinated information flow for the PH/VS STM subsystems as they interact with retrieval of relevant information from long-term storage.

Extant experimental evidence indicates that the CE and the PH STM subsystem make significant, independent contributions to children's applied mathematical problem-solving skills (Swanson and Fung 2016; Titz and Karbach 2014). Evidence for the role of VS STM in applied problem solving is equivocal, with most (e.g., Menon 2016; Metcalfe et al. 2013; Sarver et al. 2012; Swanson and Jerman 2006) but not all studies (Bull et al. 1999; Swanson and Fung 2016) reporting significant relations with applied mathematical abilities.

Despite the large magnitude WM deficits identified in children with ADHD and well-established relations between WM and applied mathematical problem solving, few studies have examined whether ADHD-related math problem solving difficulties reflect deficient domain general, higher-order CE processes and/or inadequate PH/VS STM processes. Several studies examining these relations utilized measures combining applied problem-solving performance with basic calculation performance (Alloway et al. 2010; Fried et al. 2016; Peterson et al. 2016; Rogers et al. 2011) and found that VS STM, PH STM, and PH WM (i.e., a single task requiring PH STM and CE together) contribute to applied problem solving/calculation performance in children with ADHD. The conventional practice of combining applied problem solving and calculation performance into a single metric, although informative, is contraindicated given (a) the different cognitive processes implicated in the two mathematical skills (Swanson et al. 2008) and (b) evidence that calculation abilities are a necessary but insufficient skill for solving mathematical word problems (Swanson and Fung 2016; Zentall and Ferkis 1993).

Only three studies have examined the extent to which WM processes contribute to the large magnitude deficits in applied problem solving independent of calculation skills among children with ADHD. Kuhn et al. (2016) found that children with high ADHD symptomatology, with and without comorbid math disabilities, performed worse on basic calculation and PH WM tasks (i.e., PH STM and CE together); however, the extent to which PH WM contributes to the identified calculation deficits was not examined. Re et al. (2016) found that children with high teacher-rated ADHD symptoms performed significantly worse relative to typically developing children on math word problems that required CE updating and inhibition of irrelevant information. WM measures, however, were not used in the study to determine whether the findings reflected CE updating deficiencies as opposed to between-group differences in mathematical knowledge or skills. PH WM has also been reported to partially mediate the relation between ADHD symptoms and applied problem solving skills (Gremillion and Martel 2012); however, this finding may underestimate the contribution of the CE to applied problem solving among children with ADHD given the use of a backward span task to estimate PH WM.[1] In a similar vein, Rennie et al. (2014) reported that a WM composite index significantly predicted applied mathematic problem solving aptitude in early elementary school children rated low and high on ADHD symptoms. The relative contribution of the CE and PH/VS subsystem processes to math problem solving, however, could not be determined due to the use of a composite score.

An alternative explanation for ADHD-related applied problem solving difficulties is that the calculation skills required to perform the mathematical operations contained in applied word problems are underdeveloped. For example, children must learn basic operational rules, rote arithmetic facts (e.g., 3 X 4 = 12), nuanced approaches when working with decimals and fractions, and complex regrouping, borrowing, and carrying procedures. Children with ADHD evince significant difficulty executing arithmetic calculations (Rennie et al. 2014), which begin to become automatized among typically developing children in early elementary school (cf. Groen and Parkman 1972, for a review).

A more plausible explanation of ADHD-related applied problem solving difficulties involves an interaction of the two proposed underlying mechanisms. Successful mathematical calculation performance is reliant upon upstream, CE-mediated processes that enable attentional control, inhibition of irrelevant information from entering the short-term stores, retrieval of mathematical factual knowledge and problem solving algorithms from long-term memory into the focus of attention (Cowan 2005), and updating, reordering, and manipulation of the information used while completing mathematical calculations (Zentall and Ferkis 1993). Better developed calculation skills enable a greater proportion of CE resources to be dedicated toward comprehending, updating, and processing of complex mathematical word problems (Zentall and Ferkis 1993), rather than compensating for arithmetic knowledge deficiencies (e.g., counting on one's fingers).

An initial investigation of ADHD-related calculation deficits and WM as possible contributors to applied problem solving deficits reported that PH WM (i.e., PH STM and CE together) significantly mediated ADHD-related calculation differences after controlling for the mediational influences of parent-rated inattention (Antonini et al. 2016). The Rennie et al. (2014) study discussed previously found that WM performance was a significant predictor of calculation performance among those with high teacher-rated symptomatology, indicating that one or more WM components may be implicated in ADHD-related calculation difficulties. No study to date has fractionated the CE from PH/VS STM to determine the extent to which calculation difficulties, independently or in conjunction with WM processes, contribute to ADHD-related applied problem solving difficulties. Understanding the unique and potentially interactive contribution of individual WM processes and calculation abilities to children's applied problem solving skills represents a critical first step for designing evidence based interventions that target implicated mathematical and/or WM component deficiencies in children with ADHD.

The current study investigates several hypotheses related to understanding the relative contributions of WM component processes and mathematical calculation skills to applied mathematical solving difficulties in children with ADHD. CE was expected to fully attenuate the diagnostic status to applied problem solving relation while PH STM, VS STM, and math calculation were hypothesized to partially attenuate the relation based on extant research. We also planned to model math calculation in tandem with CE, PH STM, and/or VS STM if they serve as significant simple mediators to provide a more conceptually balanced explanation of the diagnostic status to applied problem solving relation.

Method

Participants

The sample comprised 69 boys aged 8 to 12 years ($\overline{X}$ = 9.69, *SD* = 1.27), recruited by or referred to a children's learning clinic through community resources (e.g., referrals from pediatricians, community mental health clinics, school systems, and self-referral). The 8 to 12 years age range was selected to capture the onset and overlap of STM and CE abilities (Tillman et al. 2011). Sample race and ethnicity included 49 Caucasian Non-Hispanic (71%), 13 Hispanic English speaking (19%), four bi- or multi-racial (6%), and three African American (5%) 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* = 36), and typically developing boys (*n* = 33) 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, autism spectrum, or depressive disorders, or (d) Full Scale IQ score ≤ 85 were excluded.

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

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).

Thirty-six boys meeting the following criteria were included in the ADHD-Combined Type group: (1) an independent diagnosis by the directing clinical psychologist using DSM-5 criteria for ADHD-Combined Type based on K-SADS interview with parent and child; (2) parent ratings of at least 2 *SD*s above the mean on the Attention-Deficit/Hyperactivity Problems DSM-Oriented scale of the Child Behavior Checklist (CBCL; Achenbach and Rescorla 2001), or exceeding the criterion score for the parent version of the ADHD-Combined subtype subscale of the Child Symptom Inventory-4: Parent Checklist (CSI-P; Gadow et al. 2004); and (3) teacher ratings of at least 2 *SD*s above the mean on the Attention-Deficit/Hyperactivity Problems DSM-Oriented scale of the Teacher Report Form (TRF; Achenbach and Rescorla 2001), or exceeding the criterion score for the teacher version of the ADHD-Combined subtype subscale of the Child Symptom Inventory-4: Teacher Checklist (CSI-T; Gadow et al. 2004). Sixteen (23%) of the ADHD children were on a psychostimulant regimen for treatment of their ADHD symptoms (24-h washout period prior to each testing session), and eight (22%) met diagnostic criteria for Oppositional-Defiant Disorder (ODD). Children comorbid for Specific Learning Disorder with Impairment in Mathematics were included in light of high comorbidity rates among the two disorders (e.g., 20%; DuPaul et al. 2013) coupled with concerns regarding the generalizability of findings should comorbid children be excluded.

Thirty-three boys met the following criteria and were included in the typically developing group: (1) no evidence of any clinical disorder based on parent and child K-SADS interview; (2) normal developmental history by parental report; (3) ratings within 1.5 *SD*s of the mean on all CBCL and TRF scales; and (4) parent and teacher ratings within the non-clinical range on all CSI subscales.[2]

[2] Scores for one TD child exceeded 1.5 SDs on one of the two parents' but not teachers' rating scales. Parent interview revealed no significant ADHD symptoms or symptoms associated with other clinical disorders for the child. Six children with ADHD had subthreshold scores on teacher-rated hyperactivity/impulsivity. Follow-up clinical interviews, however, indicated the subthreshold symptoms were attributable to substantial psychostimulant effects while they were rated, and that all children demonstrated a history of significant, persistent levels of hyperactivity/impulsivity both at home and at school.

Procedures

The WM tasks (described below) were programmed using SuperLab Pro 2.0 (Cedrus Corporation, 2002) and administered as part of a larger battery that required the child's presence for approximately 3 h per session across four consecutive Saturday assessment sessions. Participants completed all tasks while seated alone, approximately 0.66 m from a computer monitor, in an assessment room. Performance was monitored at all times by the examiner, who was stationed just outside the child's view to provide a structured setting while minimizing performance improvements associated with examiner demand characteristics (Power 1992). All participants received brief (2–3 min) breaks following each task, and preset longer (10–15 min) breaks after every two to three tasks to minimize fatigue. The Kaufman Test of Educational Achievement 1st or 2nd edition (KTEA-I-Normative Update; Kaufman and Kaufman 1998; KTEA-II; Kaufman and Kaufman 2004) was administered during two separate weekday testing sessions to minimize fatigue. The changeover to the second edition was due to its release during the study and to provide parents the most up-to-date educational evaluation possible.

Measures

Applied Problem Solving Task Age-corrected, standardized scores from the Mathematics Applications subtest of the KTEA-I-NU (Kaufman and Kaufman 1998) and the Math Concepts and Applications subtest of the KTEA-II (Kaufman and Kaufman 2004) served as the dependent variable to measure the extent to which children were able to apply learned mathematical concepts to real-world scenarios ($r = 0.83$ between the two versions; Kaufman and Kaufman 2004). Both versions of the task require children to solve increasingly complex mathematical word problems. The examiners (trained doctoral level graduate students) orally presented word problems while providing a visible prompt (e.g., graph, visual aid) that remained visible to the child while responding to the questions. Commensurate with standardized procedures, children were provided a blank paper to perform calculations when necessary. Answers were provided orally to the examiner and recorded manually on a standardized sheet. The psychometric properties and expected patterns of relationships between the KTEA-I-NU Mathematics Applications subtest, the KTEA-II Math Concepts and Application subtest, and other measures of educational achievement are well established (cf. Kaufman and Kaufman 1998, 2004).

Math Calculation Task Age-corrected, standardized Math Computation subtest scores from the KTEA-I-NU (Kaufman and Kaufman 1998) or KTEA-II (Kaufman and Kaufman 2004) were used to assess math computational skills ($r = 0.77$ between the two versions; Kaufman and Kaufman 2004). The subtest required children to solve increasingly complex math operations printed in an individual workbook. Children were instructed to indicate their answers in the workbook which were recorded manually by the examiner for accuracy on a standardized sheet. The psychometric properties and expected patterns of relationships between the KTEA Math Computation subtest and other measures of educational achievement are well established (cf. Kaufman and Kaufman 1998, 2004).

Working Memory Tasks The working memory tasks used in the current study are identical to those described by Rapport et al. (2008).[3] Each child was administered four phonological conditions (i.e., set sizes 3, 4, 5, and 6) and four visuospatial conditions (i.e., set sizes 3, 4, 5, and 6) across the four testing sessions. The four working memory set size conditions each contained 24 unique trials of the same stimulus set size, and were counterbalanced across the four testing sessions to control for order effects and potential proactive interference effects across set size conditions. Average stimuli correct per trial served as the dependent variable for the WM tasks. Previous studies of ADHD and typically developing children reveal large magnitude between-group differences on these tasks (Rapport et al. 2008). Past investigations report strong reliability and validity of the PH WM task evidenced by high internal consistency ($r = 0.82$ to 0.97), significantly large correlations ($r = 0.50$ to 0.71) with established measures of working memory such as the WISC-IV Working Memory Index, (Alderson et al. 2015; Raiker et al. 2012), and the expected pattern of relations between the isolated CE construct and ecologically valid outcomes such as objectively measured activity level (Rapport et al. 2009a; b), attentive behavior (Kofler et al. 2010), and impulsivity (Raiker et al. 2012).

Phonological working memory (PH WM). The PH WM tasks are similar to the Letter-Number Sequencing subtest on the WISC-IV (Wechsler 2003), and assess phonological working memory based on Baddeley's (2007) model. Children were presented a series of jumbled numbers and a capital letter on a computer monitor. Each number and letter (4 cm height) appeared on the screen for 800 ms, followed by a 200 ms interstimulus interval. The letter never appeared in the first or last position of the sequence to minimize potential primacy and recency effects, and trials were counterbalanced to ensure that letters appeared an equal number of times in the other serial positions (i.e., position 2, 3, 4, or 5). Children were instructed to recall the numbers in order from smallest to largest, and to say the letter last (e.g., 4 H 6 2 is recalled correctly as 2 4 6 H). All children completed five practice trials prior to each administration and achieved the minimum of 80% accuracy on training trials. Two trained research assistants, shielded from the participant's view, recorded oral responses independently. Interrater reliability was calculated for all task conditions for all children, and ranged from 0.98 to 0.99.

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

Working memory factors. Estimates of the central executive (CE), phonological short-term memory (PH STM), and visuospatial short-term memory (VS STM) were computed at each set size. Briefly, the PH and VS STM systems are functionally and anatomically independent, with the exception of a shared (domain-general) CE controller (Baddeley 2007). Statistical regression techniques were consequently employed to provide reliable estimates of the CE and its subsidiary PH and VS STM subsystems. Precedence for using shared variance to statistically derive CE and/or PH/VS STM variables is found for working memory components in Colom et al. (2005), Engle et al. (1999), Kane et al. (2004), Rosen and Engle (1997), and Swanson and Kim (2007).

PH/VS STM factors. PH STM composite scores were computed by averaging each child's score across set sizes using the following procedure. Scores on the VSWM task were regressed out of scores on the PHWM task to remove common variance associated with the domain-general central executive (see Fig. 1). The four PH STM scores were then fixed to one factor via principle components factor analysis (factor loadings = 0.62 to 0.81) using scores at each of the four set sizes to provide an overall estimate of the contribution of PH STM independent of shared CE influences. A complementary procedure was performed whereby scores on the PHWM task were regressed out of scores on the VSWM and fixed to one factor (factor loadings = 0.58 to 0.75) to obtain an overall estimate of VS STM independent of CE influences.

CE factor. Two unstandardized predicted scores were computed by regressing VSWM scores onto PHWM scores at each set size, and vice versa. The two scores at each set size were averaged to provide an estimate of CE functioning at each set size. These four CE scores were then fixed to one factor via principle components factor analysis (factor loadings = 0.76 to 0.86) to provide an overall estimate of CE independent of the two STM subsystems.

[3] PH WM and VS WM performance data for a subset of the current sample were used in separate studies to evaluate conceptually unrelated hypotheses (Alderson et al. 2010, 2012; Friedman et al. 2017; Kofler et al. 2010, 2011, 2014; Raiker et al. 2012; Rapport et al. 2008, Rapport et al. 2009a, b; Sarver et al., 2015). We have not previously reported the Applied Problem Solving or Math Calculation data or their associations with our WM tasks for any children in the current sample.

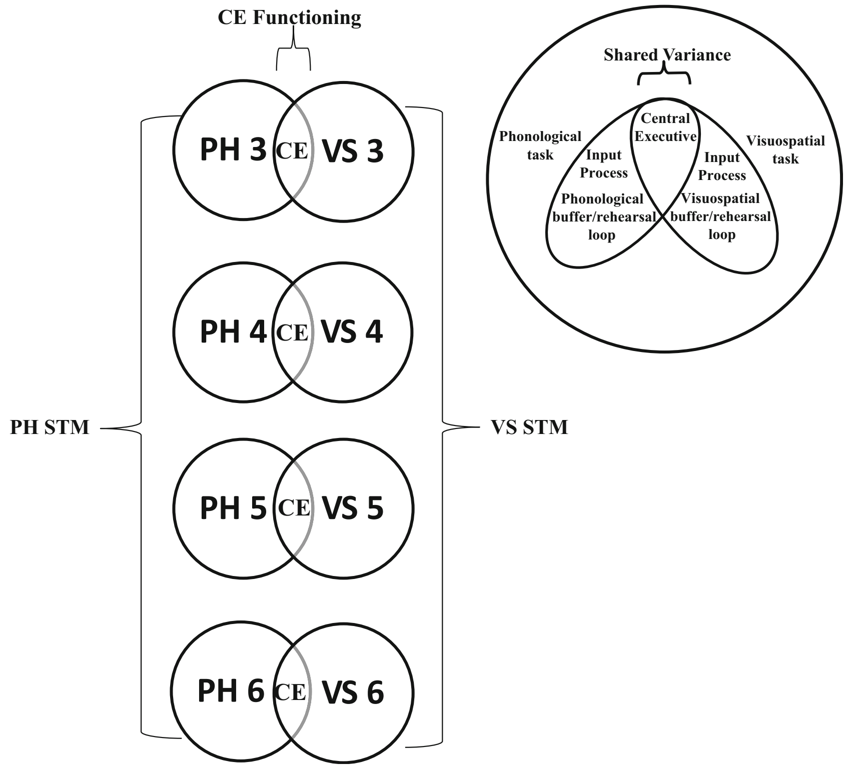

Fig. 1 Schematic depicting regression-based technique to isolate shared and unique variance in the PHWM and VSWM tasks to provide reliable estimates of the CE and its subsidiary PH STM and VS STM subsystems. The CE was estimated by regressing the lower-level subsystem processes onto each other based on extensive evidence that shared variance between the two measures (PH WM, VS WM) reflects the domain-general, higher-order supervisory mechanism for the two processes (Colom et al. 2005; Engle et al. 1999; Kane et al. 2004; Rosen and Engle 1997; Swanson and Kim 2007). Two predictor scores at each set size were averaged subsequently to provide an estimate of the CE. Unshared variance provides residual estimates of PH STM and VS STM functioning independent of CE influences

Measured Intelligence and Socioeconomic Status Children were administered the WISC-III or -IV to obtain an overall estimate of intellectual functioning based on each child's estimated Full Scale IQ (FSIQ; Wechsler 2003). The changeover to the fourth edition was due to its release during the course of the study and to provide parents with the most up-to-date intellectual evaluation possible. Hollingshead Four Factor Index of Social Status (Hollingshead 1975) was used to calculate SES based on parental education, occupation, age, and marital status. Raw scores range from 6 to 88 with higher scores indicating greater SES.

Results

Power Analysis

A large magnitude effect size was predicted based on established relations between ADHD and Working Memory (*d*s = 1.89, 2.31; Rapport et al. 2008), ADHD and Math Calculation ($d = 0.91$; Alloway et al. 2010), Working Memory and Applied Problem Solving ($r = 0.53$; Swanson and Kim 2007), and Math Calculation and Applied Problem Solving ($r = 0.65$; Kaufman and Kaufman 2004). Mediation analysis using bias-corrected bootstrapping requires 34 total participants to achieve 0.80 power (Fritz and MacKinnon 2007) and 69 boys participated in the current study.

Preliminary Analysis

All independent, dependent, and mediating variables were screened for multivariate outliers using Mahalanobis distance tests ($p < 0.001$) and univariate outliers as reflected by scores exceeding 3.5 standard deviations from the mean in either direction. No significant outliers were identified. As expected, scores on the parent and teacher behavior rating scales were significantly higher for the ADHD group relative to the typically developing group (see Table 1). Boys with ADHD and typically developing boys did not differ on age ($p = 0.10$) or SES ($p = 0.10$).[4] There was a small but significant between-group difference in FSIQ ($p = 0.02$). FSIQ was not analyzed as a covariate, however, because it shares significant variance with WM and would result in removing substantial variance associated with working memory from working memory (Dennis et al. 2009; Miller and Chapman 2001).[5] Consistent with past studies (e.g., Rapport et al. 2008), between-group

[4] SES and age were examined as potential covariates of the simple and serial mediation models presented below. Neither SES nor age were significant covariates of the model's mediators or dependent variables, and inclusion of the covariates did not affect the pattern or interpretation of the results. Simple model results with no covariates are reported to allow B-weights to be interpreted as Cohen's deffect sizes when predicting from a dichotomous grouping variable(Hayes 2009).

[5] Alternative approaches were considered but not adopted because they share substantial variance with WM (e.g., the WISC-IV General Ability Index (GAI) is comprised of the Verbal Comprehension and Perceptual Reasoning Indices, and shares 25% to 40% of variance with WM).

Table 1 Sample and demographic variables

Variable	ADHD		Typically Developing				
	$\overline{X}$	*SD*	$\overline{X}$	*SD*	*t*	Cohen's *d*	Min-Max
Age	9.45	1.18	9.96	1.34	1.68	−0.41	7.92–12.92
FSIQ	104.33	9.92	110.42	11.98	2.31*	−0.55	87–136
$FSIQ_{res}$	−0.03	0.90	0.03	1.09	0.24	−0.06	−2.79–2.36
SES	48.67	10.60	52.82	9.69	1.69	−0.41	15–66
CBCL AD/HD DSM Problems	72.56	6.91	53.09	6.49	−12.04***	2.90	50–96
TRF AD/HD DSM Problems	67.94	7.76	51.24	10.27	−7.66***	1.83	50–89
CBCL Internalizing Problems	60.47	9.64	49.39	10.78	−4.51***	1.08	34–73
TRF Internalizing Problems	54.39	9.64	46.36	8.58	−3.64***	0.88	38–75
CSI-P: ADHD, Combined	76.50	9.42	47.91	10.24	−12.08***	2.91	37–95
CSI-T: ADHD, Combined	69.14	9.37	47.42	7.02	−10.82***	2.62	39–85
Applied Problem Solving	101.11	12.92	114.06	13.93	4.01***	−0.96	70–134
Math Calculation	94.94	12.48	105.15	12.88	3.34***	−0.81	67–128
Phonological STM Factor Score	−0.41	1.06	0.45	0.70	3.95***	−0.96	−2.95–1.87
Visuospatial STM Factor Score	−0.31	0.97	0.34	0.93	2.84**	−0.68	−2.34–1.57
Central Executive Factor Score	−0.60	0.88	0.65	0.67	6.62***	−1.60	−2.40–1.81

ADHD attention-deficit/hyperactivity disorder, *CBCL* Child Behavior Checklist, *CSI-P* Child Symptom Inventory: Parent severity *T*-scores, *CSI-T* Child Symptom Inventory: Teacher severity *T*-scores, *FSIQ* Full Scale Intelligence Quotient, $FSIQ_{res}$ Full Scale Intelligence Quotient with working memory removed, *SES* socioeconomic status, *STM* short-term memory, *TRF* Teacher Report Form

* $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$

differences in FSIQ were tested by removing reliable variance associated with the WM CE factor (described above) from FSIQ and then examining between-group differences in FSIQ without the influence of the CE. Results revealed that between-group differences in this residual FSIQ score were not significant ($p = 0.81$). As a result, simple model results with no covariates are reported.

Tier I: Intercorrelations

Zero-order intercorrelations between all factor scores were computed to substantiate consideration of indirect influences of the Diagnostic Status to Applied Problem Solving relation. All correlations for Tier II simple mediation models showed the expected relations (see Table 2); therefore, all three WM components and Math Calculation were retained in Tier II.

Tier II: Simple Mediation Analyses

Separate simple mediation models were tested to examine the extent to which each of the significantly related Tier I WM and Math Calculation variables attenuated the relationship between Diagnostic Status and Applied Problem Solving skills. All analyses were completed using bias-corrected bootstrapping to minimize Type II error as recommended by Shrout and Bolger (2002). Bootstrapping was used to establish the statistical significance of all total, direct, and indirect effects. All continuous variables were standardized *z*-scores based on the full sample to facilitate between-model and within-model comparisons and allow unstandardized regression coefficients (*B* weights) to be interpreted as Cohen's *d* effect sizes when predicting from a dichotomous grouping variable (Hayes 2009). The PROCESS script for SPSS (Hayes 2013) was used for all analyses, and 10,000 samples were derived from the original sample ($N = 69$) by a process of resampling with replacement (Shrout and Bolger 2002). Effect ratios (indirect effect divided by total effect) were calculated to estimate the proportion of each significant total effect that was attributable to the mediating pathway (indirect effect). Cohen's *d* effect sizes, standard errors, 95% confidence intervals, and effect ratios are shown in Fig. 2.

Examination of the total effect (Fig. 2, c paths) revealed that Diagnostic Status (TD, ADHD) was related significantly to Applied Problem Solving, $d = -0.87$; 95% CI (−1.31, −0.44), such that a diagnosis of ADHD was associated with large magnitude Applied Problem Solving differences prior to accounting for potential mediators. PH STM (Fig. 2a) and VS STM (Fig. 2b) were not significant mediators of the Diagnostic Status to Applied Problem Solving relation. CE was a significant, full mediator of ADHD-related Applied Problem Solving differences, $d = -0.52$; 95% CI (−0.96, −0.21), and accounted for 60% of the variance in the relation (Fig. 2c). Math Calculation (Fig. 2d) was a significant, partial mediator of ADHD-related Applied Problem Solving differences, $d = -0.52$; 95% CI (−0.87, −0.23), and accounted for 60% of the variance in the relation.

Table 2 Zero-order correlations

		1	2	3	4	5	6	7	8
1.	Diagnostic status (TD = 0, ADHD = 1)								
2.	Age	−0.20* (−0.42, −0.04)							
3.	SES	−0.20* (−0.42, −0.03)	−0.02 (−0.24, 0.20)						
4.	FSIQ	−0.27* (−0.49, −0.40)	−0.04 (−0.31, 0.22)	0.32* (0.08, 0.53)					
5.	Central Executive	−0.63* (−0.74, −0.50)	0.37* (0.17, 0.55)	0.25* (−0.06, 0.50)	0.39* (0.19, 0.57)				
6.	PH STM	−0.43* (−0.61, −0.24)	0.15 (−0.07, 0.36)	0.10 (−0.13, 0.34)	0.12 (−0.10, 0.34)	0.63* (0.49, 0.74)			
7.	VS STM	−0.33* (−0.53, −0.11)	0.31* (0.08, 0.52)	0.22 (−0.50, 0.46)	0.36* (0.10, 58)	0.60* (0.44, 0.75)	−0.23* (−0.43, −0.003)		
8.	Math Calculation	−0.38* (−0.56, −0.17)	−0.14 (−0.35, 0.08)	0.35* (0.14, 0.53)	0.53* (0.36, 0.68)	0.47* (0.22, 0.73)	0.31* (0.11, 0.49)	0.28* (0.01, 0.51)	
9.	Applied Problem Solving	−0.44* (−0.63, −0.24)	−0.06 (−0.30, 0.17)	−0.25* (0.05, 0.42)	0.57* (0.37, 0.73)	0.53* (0.35, 0.67)	0.32* (0.07, 0.54)	0.34* (0.08, 0.56)	0.76* (0.63, 0.84)

ADHD attention-deficit/hyperactivity disorder, *PH STM* phonological short-term memory, *SES* Socioeconomic Status, *FSIQ* Full Scale IQ, *TD* typically developing, *VS STM* visuospatial short-term memory. Correlations reflect bias corrected, bootstrapped Pearson's Correlation coefficients with 10,000 samples derived from the original sample. Ninety-five percent confidence intervals are presented in parentheses below the corresponding correlation coefficient. *Correlation is significant based on confidence intervals that do not include 0.0 (Shrout and Bolger 2002)

Tier III: Serial Mediation Analyses

In the final analytic tier, we examined the extent to which the significant Tier II mediators (CE and Math Calculation), alone and interactively, account for between-group differences in Applied Problem Solving by evaluating a serial mediation model using the PROCESS script for SPSS (Hayes 2014). CE was entered into the model first based on theoretical grounds (Baddeley 2007) that CE-governed processes are up-stream of math calculation processes, rather than vice versa.

The total effect of Diagnostic Status on Applied Problem Solving, $d = -0.87$; Fig. 3, path c, was significantly attenuated when CE and Math Calculation were included as mediators, $d = -0.19$; Fig. 3, path c', such that the combined effect of all three mediating pathways accounted for 79% of the Diagnostic Status/Applied Problem Solving relation, and the direct effect of Diagnostic Status on Applied Problem Solving was no longer detectable (95% CI included 0.0, indicating no effect). This combined effect was carried primarily by the mediating role of CE through its impact on Math Calculation, $d = -0.31$; Fig. 3, CE ➔ Math Calculation Indirect Effect, such that their joint influence explained 36% of ADHD-related Applied Problem Solving difficulties. CE ability alone (i.e., independent of the influence of Math Calculation) did not significantly explain between-group differences in Applied Problem Solving, $d = -0.21$; 95% CI included 0.0; Fig. 3, CE Indirect Effect, but accounted for a small proportion (24%) of the relation between Diagnostic Status and Applied Problem Solving. Similarly, Math Calculation alone (i.e., independent of the influence of CE) did not significantly explain between-group differences in Applied Problem Solving, $d = -0.17$; Effect Ratio = 0.20; 95% CI included 0.0; Fig. 3, Math Calculation Indirect Effect. Interestingly, between group differences in Math Calculation skills were fully attenuated after accounting for variance due to CE ability, $d = -0.26$; 95% CI included 0.0; Fig. 3, Path a_2. Collectively, these findings indicate that the moderate magnitude influence of CE and Math Calculation on Applied Problem Solving observed in Tier II is largely driven by CE's impact on the children's ability to perform arithmetic calculations. Taken together with the high effect ratio (79% of variance explained) and nonsignificant, residual association between Diagnostic Status and Applied Problem Solving, these findings indicate that the interactive effects of CE deficits and down-stream calculation difficulties play an important role in understanding the applied problem solving difficulties commonly observed among children with ADHD.

Discussion

The current study is the first to quantify the relative contribution of individual working memory components (i.e., CE, PH STM, and VS STM) to applied mathematical problem solving difficulties among children with ADHD while concomitantly examining the unique and shared influence of calculation skills. Despite the significant correlations between PH/VS STM and applied problem solving, neither VS STM nor PH STM served as significant mediators for ADHD-related applied mathematic problem solving differences. These findings suggest that, although the domain-specific storage/rehearsal subsystems make significant contributions to children's ability to correctly solve applied mathematical problems, they are insufficient mechanisms for explaining the large magnitude

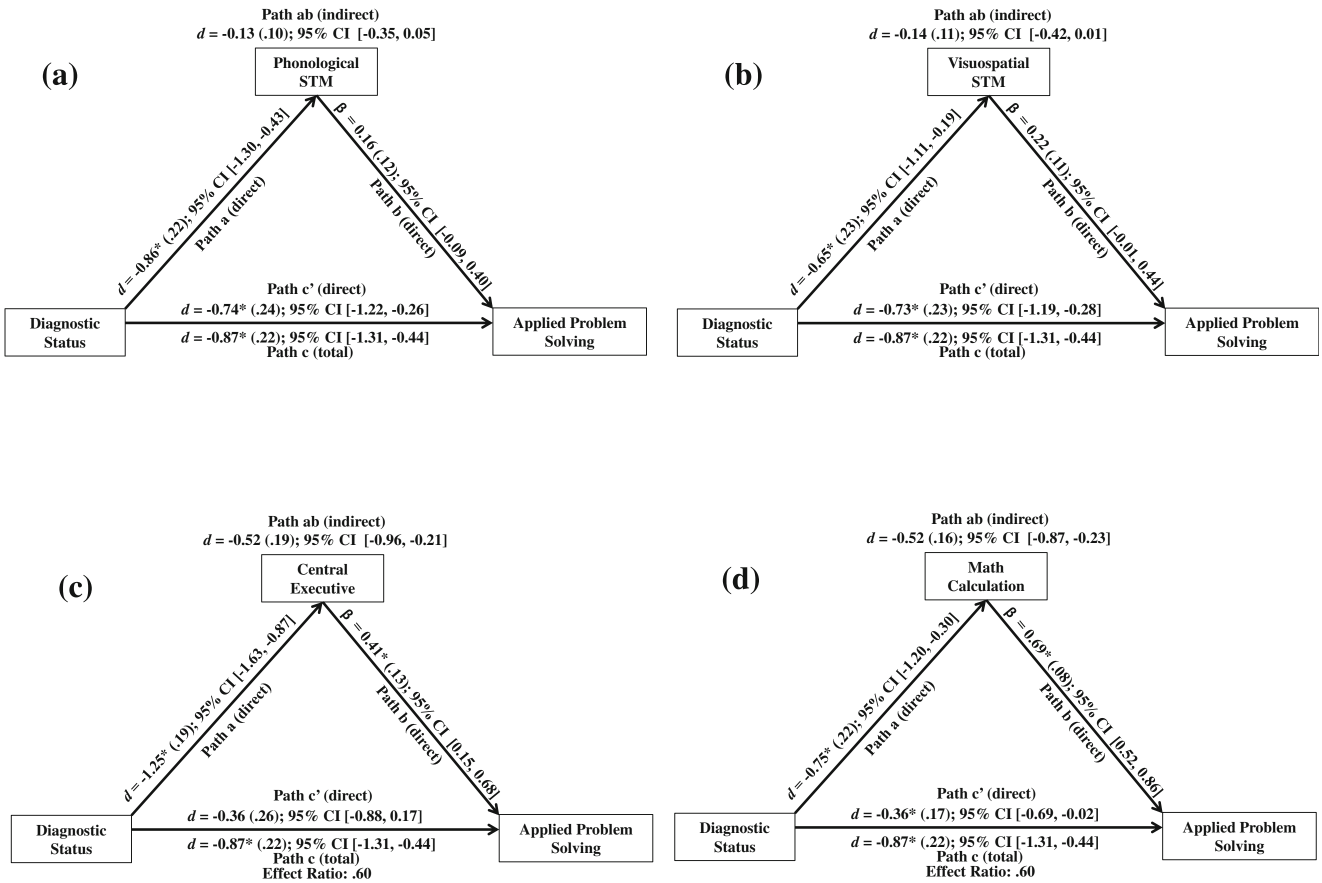

Fig. 2 CI = confidence interval, STM = short-term memory. Schematics depicting the effect sizes, standard errors and *B* coefficients of the total, direct, and indirect pathways for the mediating effect of **a** Phonological Short-Term Memory, **b** Visuospatial Short-Term Memory, **c** Central Executive, and **d** Math Calculation on Applied Problem Solving. Cohen's *d* for the c and c' pathways reflects the impact of ADHD diagnostic status on Applied Problem Solving before (path c) and after (path c') taking into account the mediating variable. *Effect size (or *B*-weight) is significant based on 95% confidence intervals that do not include 0.0 (Shrout and Bolger 2002); values for path b reflect *B*-weights due to the use of two continuous variables in the calculation of the direct effect

applied problem solving difficulties children with ADHD evince both in the current study and extant literature. The lack of significant PH STM mediation was unexpected. For example, Gremillion and Martel (2012) found that PH STM and semantic language partially mediated the relationship between diagnostic status and applied problem solving after controlling for nonverbal intelligence. Our regression-based approach for isolating CE from PH STM to minimize shared variance between the two variables (Engle et al. 1999) may have contributed to the discrepant findings between the two studies, and suggests that the active processing component (CE) rather than the storage function (PH STM) of WM plays a more vital role in children's ability to solve applied math problems.

The non-significant VS STM was also unexpected given the prominent role of VS STM processes in children's applied problem solving skills (e.g., storing visual imagery, maintaining spatial relations, organizing visual information) and supporting evidence suggesting its involvement (Menon 2016; Metcalfe et al. 2013; Sarver et al. 2012; Swanson and Jerman 2006). The discrepant findings, however, may reflect the presentation modality used in the current study. Although children were provided a visual prompt (e.g., graph, chart, or picture), applied problems were read orally commensurate with standardized instructions, which in turn, may have diminished the extent to which VS STM processing was needed to solve applied math problems. This methodology was adopted over alternative approaches that require children to read applied problems based on (a) best-practice recommendations to minimize the influence of reading comprehension (Zentall and Ferkis 1993) given the large magnitude relations between applied problem solving and reading comprehension (Swanson and Jerman 2006); and (b) concerns that statistically controlling for reading comprehension skills would remove variance attributable to the CE given its prominent role in ADHD-related reading comprehension difficulties (Friedman et al. 2017).

As hypothesized, CE and math calculation skills each mediated the relation between diagnostic status and applied mathematic problem solving skills when modeled separately. This finding is consistent with previous studies documenting

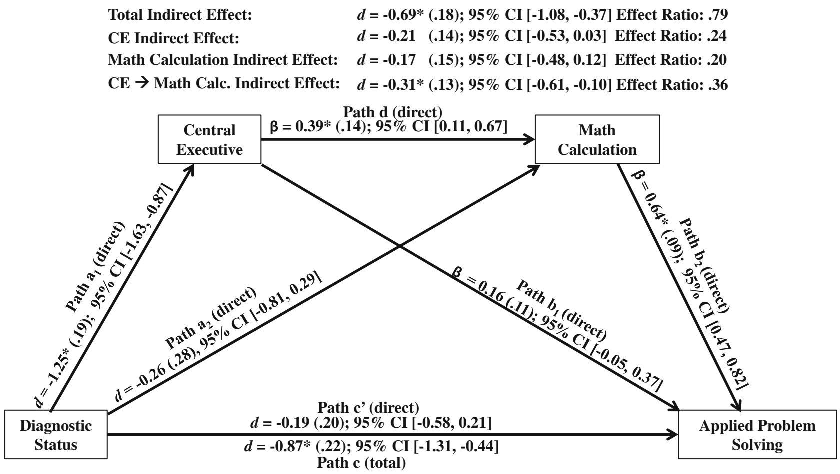

Fig. 3 Calc. = Calculation; CI = confidence interval. Schematic depicting the effect sizes, standard errors, and *d* coefficients of the total, direct, and indirect pathways for serial mediation of Central Executive and Math Calculation on the relationship between Diagnostic Status and Applied Problem Solving. Cohen's *d* for the c and c' pathways reflects the impact of ADHD Diagnostic Status on Applied Problem Solving before (path c) and after (path c') taking into account the mediating variables. *Effect size (or *B*-weight) is significant based on 95% confidence intervals that do not include 0.0 (Shrout and Bolger 2002); values for path b reflect *B*-weights due to the use of two continuous variables in the calculation of the direct effect. CE Indirect Effect represents the mediating effect of Central Executive independent of Math Calculation on Applied Problem Solving. Math Calculation Indirect Effect represents the mediating effect of Math Calculation independent of the Central Executive on Applied Problem Solving. CE ➔ Math Calculation Indirect Effect represents the mediating effect of the shared influence of Central Executive and Math Calculation on Applied Problem Solving. Total Indirect Effect represents the collective influence of all three mediation pathways. The three indirect effects do not sum to the total indirect effect due to rounding

involvement of the two processes in applied problem solving (Zentall and Ferkis 1993), and warranted examining whether they would remain independent influences or are more accurately portrayed as interacting processes (Swanson and Fung 2016). The ensuing serial mediation model revealed that between group differences in mathematic calculation skills are fully attenuated after accounting for CE. This finding, coupled with the significant CE ➔ Math Calculation indirect effect, suggests that CE and mathematic calculation skills act in tandem to fully attenuate between-group differences in applied problem solving and account for 79% of the relation.

The large-magnitude attenuation driven by the shared influence of the two cognitive abilities likely reflects a complex interplay among CE processes and math-related information activated from long-term memory. Our WM tasks require multiple CE processes, including sustained attentional focus and interference control, reordering/sequencing, and a moderate interplay with long-term memory to activate knowledge of numbers and letters into the subsystem stores (Simmons et al. 2012; Swanson and Fung 2016). In contrast, math calculation skills independent of CE influences, largely reflect the extent to which mathematical rules, algorithms, and related problem solving processes are coded and can be activated from long-term memory (Barrouillet and Lépine 2005). The finding that diagnostic status/applied math relation was accounted for by the interaction rather than the independent influences of these variables suggests several possibilities relevant to understanding ADHD-related difficulties in solving applied math problems. One possibility is that underdeveloped CE-related interference control allows irrelevant internal and/or external information to gain access to and interfere with math calculation information temporarily held in the PH STM (Swanson and Fung 2016); however, the lack of PH STM involvement in ADHD-related applied problem solving differences renders this explanation implausible. A second possibility is that basic attentional control is limited in children with ADHD secondary to default mode network dysfunction (e.g., Fassbender et al. 2009) and diminishes focused attention while performing arithmetic calculations necessary for successful applied problem solving. 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). Further, one of the central tenets of the default mode network hypothesis has been called into question in a recent meta-analytic review indicating that intraindividual variability in reaction times occurs both within and outside of frequencies predicted by the theory (Karalunas et al. 2013). Moreover, the KTEA Math Calculation and Applied Problem subtests were administered individually by a skilled examiner in a quiet setting via standardized instructions to minimize inattentiveness and maximize performance. Finally, the significant interplay between CE ability and math calculation skills may reflect deficits in multiple CE processes that impact the retrieval and updating of math calculation-related information from long-term memory so that knowledge can be connected with and applied to the mathematical word problem. The current study, however, did not fractionate the distinct CE-related processes to elucidate their unique and/or interactive contributions to ADHD-related applied problem solving difficulties, but such distinctions warrant investigation. Future studies may further benefit from examining the extent to which expertise in calculation skills may moderate the relation between WM and applied problems—viz., children with better-developed calculation skills may allocate fewer CE resources to solve applied problems than children with poorer calculation skills.

Several caveats merit consideration despite methodological (e.g., stringent, multi-method/multi-informant diagnostic procedures; multiple tasks to estimate WM constructs; age range) and statistical (e.g., bootstrapped mediation) refinements. Due to the well-documented gender differences related to ADHD symptom presentation (Williamson and Johnston 2015), neurocognitive deficits (Bálint et al. 2009), and neuroanatomy (Dirlikov et al. 2015), the current study examined cognitive and mathematical problem solving skills exclusively in boys. The results require replication using larger and more diverse samples of children that include girls, preschoolers, adolescents, and additional ADHD presentations, as well as children with comorbid Specific Learning Disability in Mathematics. Additional benefit may also accrue by examining the extent to which the current findings extend to children diagnosed with clinical disorders where WM performance deficits are suspected, such as neurodevelopmental disabilities (Luna et al. 2002), depression (Harvey et al. 2004), and anxiety (Tannock et al. 1995). Identifying shared cognitive contributors underlying applied problem solving difficulties among disorders, in turn, may prove useful for designing/adopting a precision medicine-based approach rather than the disorder specific approach used currently (Insel 2014). Moreover, age-dependent changes in WM abilities may differentially affect applied solving skills (Brocki and Bohlin 2004, 2006). Although age was not a significant covariate of our model's mediators, it is possible that certain WM abilities identified in narrower age ranges (e.g., 7.6–9.5, 9.6–11.5) may predict age-specific applied math difficulties more precisely. Given the importance of age to the development of different WM abilities, future analysis of separable WM abilities (e.g., interference control, updating, dual-processing) across age ranges such as those described in Brocki and Bohlin (2004) may reveal particular patterns of ADHD-related applied problem solving difficulties. Finally, the reported applied problem solving to math calculation relation may be overestimated moderately due to drawing both subtests from the same achievement battery. The KTEA inter-battery correlation for the two subtests (r = 0.70; Kaufman and Kaufman 2004), however, is nearly identical to the intra-battery correlation between KTEA Math Concepts and Applications and WIAT-II Basic Calculation (r = 0.75) and suggests that the two skills are highly correlated because knowledge of basic math calculations is requisite for solving applied math problems.

Complementary neuroimaging studies are warranted to determine the extent to which overlapping patterns of activation during WM and mathematics tasks identified in children with Specific Learning Disorder in Mathematics and in community samples (e.g., posterior parietal, premotor, and ventral/dorsolateral prefrontal cortices; Menon 2016) are consistent in children with ADHD. Although similar activation patterns are not necessarily indicative of shared neural mechanisms, elucidation of the involved neural networks, coupled with CE and calculation performance deficits, may be used to inform the design and implementation of personalized interventions consistent with the NIMH Research Domain Criteria (RDoC) initiative (Insel 2014).

Finally, the significant contributors to applied problem solving differences identified in the current study have several clinical implications. The large magnitude applied problem solving difficulties identified in extant literature and corroborated in the present study, coupled with the non-significant or small magnitude improvement in academic achievement measures following gold-standard treatments for ADHD (viz., psychostimulants, psychosocial treatments, and their combination; Molina et al. 2009; Van der Oord et al. 2008), highlight the need for novel interventions for ADHD aimed at improving ecologically valid outcomes such as reading and math. The recent proliferation of cognitive training programs to strengthen underdeveloped executive functions such as WM has arisen from this need; however, their ineffectiveness is well documented in recent meta-analytic reviews (Rapport et al. 2013) and likely reflects their focus on training lower level PH/VS STM rather than training upper level CE processes in tandem with improving core foundational knowledge. Future cognitive training programs may prove more successful by adopting a personalized medicine approach that targets intraindividually identified cognitive and academic weaknesses given recent evidence indicating that the pattern of neurocognitive deficits varies greatly among children with ADHD (Epstein et al. 2011; Willcutt et al. 2005).

Compliance with Ethical Standards

Funding This study was conducted without external funding.

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

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

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

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