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

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APPLIED PROBLEM SOLVING IN CHILDREN WITH ADHD: THE MEDIATING ROLES OF WORKING MEMORY AND MATHEMATICAL CALCULATION

by

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ABSTRACT

The difficulties children with ADHD experience solving applied math problems (i.e., word problems) are well documented; however, the independent and/or interactive contribution of cognitive processes underlying these difficulties is 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 ability (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 ADHD-related deficits in applied math ability. 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 among these skills and CE processes.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

ADHD	Attention Deficit/Hyperactivity Disorder
CBCL	Child Behavior Checklist
CE	Central Executive
CSI-P	Child Symptom Inventory-Parent
CSI-T	Child Symptom Inventory-Teacher
FSIQ	Full Scale Intelligence Quotient
K-SADS	Kiddie Schedule for Affective Disorders and Schizophrenia
KTEA	Kaufman Test of Educational Achievement
PH	Phonological
STM	Short-Term Memory
TRF	Teacher Report Form
VS	Visuospatial
WISC	Wechsler Intelligence Scale for Children
WM	Working Memory

CHAPTER ONE: INTRODUCTION

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, Gormley, & Laracy, 2013; Frazier, Youngstrom, Glutting, & Watkins, 2007; Loe & Feldman, 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 & Birchwood, 2010; Loe & Feldman, 2007; Titz & Karbach, 2014), and decreased productivity during math-related classroom activities (Rapport, Kofler, Alderson, Timko, & DuPaul, 2009; Vile Junod, DuPaul, Jitendra, Volpe, & Cleary, 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 (Jordan, Kaplan, Ramineni, & Locuniak, 2009; Judge & Watson, 2011), delinquent behavior (Maugin & Loeber, 1996), lower high school and college graduation rates (National Longitudinal Transition Study 2, 2009), occupational skills (Mathews, Whang, & Fawcett, 1982), and socioeconomic status in adulthood (Ritchie & 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 abilities (see Zentall & Ferkis, 1993, for a review). WM is a multi-component system responsible for the 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 interfaces with long-term memory. It is also responsible for the oversight and coordination of two *memory* subsystems (i.e., phonological short-term memory [PH STM] and visuospatial short-term memory [VS STM]).

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 & Alloway, 2012; Swanson & Fung, 2016; Swanson & 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 & Fung, 2016; Swanson & Sachse-Lee, 2001). In a complementary fashion, the VS STM subsystem temporarily stores non-verbal 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 (Davis & Bamford, 1995; Simmons, Willis, & Adams, 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 & Alloway, 2012; Swanson & 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 abilities (Swanson & Alloway, 2012; Swanson & Fung, 2016; Titz & Karbach, 2014). Evidence for the role of VS STM in applied problem solving is equivocal, with most (Menon, 2016; Metcalfe, Ashkenazi, Rosenberg-Lee, & Menon, 2013; Sarver et al., 2012; Swanson & Jerman, 2006; Swanson & Sachse-Lee, 2001) but not all studies (Bull, Johnston, & Roy, 1999; Swanson & 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, Elliot, & Place, 2010; Fried et al., 2016; Peterson et al., 2016; Rogers, Hwang, Toplak, Weiss, & Tannock, 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/calculation performance in children. The conventional practice of combining applied and calculation performance into a single metric, although informative, is contraindicated given (a) the different cognitive processes implicated in the two mathematical skills (Swanson & Alloway, 2012; Swanson, Jerman, & Zheng, 2008) and (b) evidence that calculation abilities are a necessary but insufficient skill for solving mathematical word problems (Swanson & Fung, 2016; Zentall & 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. Re and colleagues (2016) found that children with 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 (i.e., CE and PH STM together) has also been reported to partially mediate the relation between ADHD symptoms and applied problem solving skills (Gremillion & 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 and colleagues (2014) reported that a WM composite index significantly predicted applied mathematic problem solving aptitude in early elementary school

[1] Studies by Rosen and Engle (1997) and others (e.g., Colom, Abad, Rebollo, & Shih, 2005; Swanson & 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.

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 comprised of CE and PH/VS STM subsidiary components.

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 (Abikoff, Courtney, Szeibel, & Koplewicz, 1996; Rennie et al., 2014; Zentall & Shaw, 1980), which begin to become automatized among typically developing children in early elementary school (cf. Groen & 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 & 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 & 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) 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 fractioned 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 to children's applied problem solving skills represents a critical first step to designing evidence based interventions that target implicated mathematical and/or WM component deficiencies in children with ADHD (Gathercole, 2014; Rapport, Orban, Kofler, & Friedman, 2013).

The current study investigates several hypotheses related to understanding the relative contributions of WM component processes and mathematical calculation skills to applied mathematical solving deficits 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 the CE in tandem with math calculation, 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.

CHAPTER TWO: METHODOLOGY

Participants

The sample comprised 69 boys aged 8 to 12 years ($\bar{x}$ = 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). Sample race and ethnicity included 49 Caucasian Non-Hispanic (71 %), 13 Hispanic English speaking (19 %), four bi- or multi-racial (5.7 %), and three African American (4.3 %) 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, or (d) Full Scale IQ score $\leq$ 85 were excluded.

Group Assignment

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

Thirty-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-IV[2] criteria for ADHD-Combined Type based on K-SADS interview with parent and child; (2) parent ratings of at least 2 *SD*s above the mean on the Attention-Deficit/Hyperactivity Problems DSM-Oriented scale of the Child Behavior Checklist (CBCL; Achenbach & Rescorla, 2001), or exceeding the criterion score for the parent version of the ADHD-Combined subtype subscale of the Child Symptom Inventory-4: Parent Checklist (CSI-P; Gadow, Sprafkin, Salisbury, Schneider, & Loney, 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 & 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, and their psychometric properties are well established (Rapport, Kofler, Alderson, & Raiker, 2008). Sixteen (23%) of the ADHD children were on a psychostimulant regimen for treatment of their ADHD symptoms (24-hour 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 not excluded given that comorbidity rates are high (e.g., 20% DuPaul et al., 2013) among the two disorders 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[3].

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[2] All participants met criteria for ADHD-Combined Presentation using DSM-5 diagnostic criteria.
[3] 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

Procedures

The WM tasks (described below) were programmed using SuperLab Pro 2.0 (2002) and were administered as part of a larger battery that required the child's presence for approximately 3 hours 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 & Kaufman, 1998; KTEA-II; Kaufman & 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 & Kaufman, 1998) and the Math Concepts and Applications subtest of the KTEA-II (Kaufman & Kaufman, 2004) served as the dependent variable to measure the extent to which children were able to apply learned mathematical concepts to real-world

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.

scenarios (r = 0.83 between the two versions; Kaufman & Kaufman, 2004). Both versions of the task require children to solve increasingly complex mathematical word problems. The examiner (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 & Kaufman, 1998; 2004).

Working Memory Tasks

The working memory tasks used in the current study are identical to those described by Rapport, Alderson, et al. (2008)[4]. Each child was administered four phonological conditions (i.e., set sizes 3, 4, 5, and 6) and four visuospatial conditions (i.e., set sizes 3, 4, 5, and 6) across the four testing sessions. The four working memory set size conditions each contained 24 unique trials of the same stimulus set size, and were counterbalanced across the four testing sessions to control for order effects and potential proactive interference effects across set size conditions. Previous studies of ADHD and typically developing children reveal large magnitude between-group differences on these tasks (Rapport, Alderson, et al., 2008). The WM tasks also have the

[4] PH WM and VS WM performance data for a subset of the current sample were used in separate studies to evaluate conceptually unrelated hypotheses (REFS removed for blind review). 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.

expected level of external validity (r = .50 to .66) with WISC-IV Digit Span STM raw scores (Raiker, Rapport, Kofler, & Sarver, 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). Children completed five practice trials prior to each administration (≥ 80% correct required). All children achieved the minimum of 80% accuracy on training trials. Two trained research assistants, shielded from the participant's view, recorded oral responses independently. Interrater reliability was calculated for all task conditions for all children, and ranged from .98 to .99.

Visuospatial Working Memory (VS WM)

Children were shown nine squares arranged in three offset vertical columns on a computer monitor. A series of 2.5 cm diameter dots (3, 4, 5, or 6) were presented sequentially in one of the nine squares during each trial such that no two dots appeared in the same square on a given trial. All but one dot that was presented within the squares was black; the exception being a red dot that never appeared as the first or last stimulus in the sequence. Children were instructed to indicate the serial position of black dots in the order presented by pressing the corresponding squares 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 using the procedures described by Rapport, Alderson, et al. (2008). Briefly, the PH and VS systems are functionally and anatomically independent, with the exception of a shared (domain-general) CE controller (Baddeley, 2007). Statistical regression techniques were consequently employed to provide reliable estimates of the CE and its subsidiary PH and VS STM subsystems. The CE was estimated by regressing the lower-level subsystem processes onto each other based on the assumption that shared variance between the two measures (PH WM, VS WM) reflects the domain-general, higher-order supervisory mechanism for the two processes. Two predictor scores were averaged subsequently to provide an estimate of the CE. Removing the common variance of the PH and VS subsidiary systems has the additional advantage of providing residual estimates of PH STM and VS STM functioning independent of CE influences. Precedence for using shared variance to statistically derive CE and/or PH/VS STM variables is found for working memory components in Colom et al. (2005), Engle, Tuholski, Laughlin, and Conway (1999), Kane et al. (2004), Rosen and Engle (1997), and Swanson and Kim (2007). Factors were created for each construct (CE [factor loadings = .76 to .86], PH [factor loadings = .62 to .81], VS [factor loadings = .58 to .75]) using scores at each of the four set sizes.

Math Calculation Task

Age-corrected, standardized Math Computation subtest scores from the KTEA-I-NU (Kaufman & Kaufman, 1998) or KTEA-II (Kaufman & Kaufman, 2004) were used to assess math computational skills ($r = 0.77$ between the two versions; Kaufman & 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 and 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 & Kaufman, 1998; 2004).

Measured Intelligence

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

Socioeconomic Status

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.

CHAPTER THREE: FINDINGS

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, Alderson, et al., 2008), ADHD and Math Calculation (*d* = 0.91; Alloway, Elliot, & Place, 2010), Working Memory and Applied Problem Solving (*r* = .53; Swanson et al., 2007), and Math Calculation and Applied Problem Solving (*r* = .65; Kaufman & Kaufman, 2004). Mediation analysis using bias-corrected bootstrapping requires 34 total participants to achieve .80 power (Fritz & 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 ($p < .001$) and univariate outliers as reflected by scores exceeding 3.5 standard deviations from the mean in either direction (Tabachnick & Fidell, 2007). 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 ($p = .10$) or SES ($p = .10$)[5]. There was a small but significant between-group difference in FSIQ ($p = .02$). 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 &

[5] SES was examined as a potential covariate of the simple and serial mediation models presented below. SES was not a significant covariate of any of the model's mediators or dependent variables, and inclusion of the covariate did not affect the pattern or interpretation of the results. In order to allow B-weights to be interpreted as Cohen's d effect sizes when predicting from a dichotomous grouping variable (Hayes, 2009), simple model results with no covariates are reported.

Chapman, 2001)[6]. Consistent with past studies (e.g., Rapport, Alderson, et al., 2008), between-group differences in FSIQ were tested by removing reliable variance associated with the CE (i.e., 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 = .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 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 abilities. All analyses were completed using bias-corrected bootstrapping to minimize Type II error as recommended by Shrout and Bolger (2002). Bootstrapping was used to establish the statistical significance of all total, direct, and indirect effects. All continuous variables were standardized z-scores based on the full sample to facilitate between-model and within-model comparisons and allow unstandardized regression coefficients (B weights) to be interpreted as Cohen's d effect sizes when predicting from a dichotomous grouping variable (Hayes, 2009). The PROCESS script for SPSS (Hayes, 2014) was used for all analyses, and 10,000 samples were derived from the original sample (N =

[6] Alternative approaches were considered but not adopted because they share considerable 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).

69) by a process of resampling with replacement (Shrout & Bolger, 2002).

Effect ratios (indirect effect divided by total effect) were calculated to estimate the proportion of each significant total effect that was attributable to the mediating pathway (indirect effect). Cohen's *d* effect sizes, standard errors, indirect effects, and effect ratios are shown in Figures 1 and 2. Ninety five percent confidence intervals were selected over 90% confidence intervals because the former are more conservative for evaluating indirect effects (Shrout & Bolger, 2002).[7]

Total Effect

Examination of the total effect (Figures 1 and 2, path c) revealed that Diagnostic Status (TD, ADHD) was related significantly to Applied Problem Solving (Cohen's d = -0.87), such that a diagnosis of ADHD was associated with large magnitude Applied Problem Solving deficits prior to accounting for the potential mediating role of CE, PH STM, VS STM, and Math Calculation processes.

Phonological Short-Term Memory Mediating ADHD Applied Problem Solving Deficits

Using simple mediation analysis conducted using ordinary least squares path analysis, a diagnosis of ADHD was associated with significantly poorer PH STM (Cohen's *d* = -0.86; Figure 1a, path a); however, PH STM was not significantly related to Applied Problem Solving independent of Diagnostic Status (β = 0.16; Figure 1a, path b). Examination of the mediation pathway (Figure 1a, path ab) revealed that the indirect effect of Diagnostic Status on Applied Problem Solving (Cohen's *d* = -0.13; 95% CI [-0.35, 0.05]) through its impact on PH STM was nonsignificant, indicating that PH STM is not a

[7]Although 90% confidence intervals are considered more conservative in determining the degree of attenuation when considering the relation between diagnostic status and the dependent variable after accounting for the mediator (i.e., full vs. partial mediation; Shrout & Bolger, 2002), recent best-practice recommendations highlight consideration of the magnitude of the indirect effect rather than full vs. partial mediation. As a result, 95% confidence intervals, which are more conservative when determining the significance of the indirect effect, were used for all mediation models (cf. Hayes 2013; Rucker, Preacher, Tormala, & Petty, 2011, for reviews.)

significant mediator of ADHD-related applied problem solving differences.

Visuospatial Short-Term Memory Mediating ADHD Applied Problem Solving Deficits

A diagnosis of ADHD was associated with significantly poorer VS STM (Cohen's *d* = -0.65; Figure 1b, path a); however, VS STM was not significantly related to Applied Problem Solving abilities independent of Diagnostic Status (β = 0.22; Figure 1b, path b). Examination of the mediation pathway (Figure 1b, path ab) revealed that the indirect effect of Diagnostic Status on Applied Problem Solving (Cohen's *d* = -0.14; 95% CI [-0.42, 0.01]) through its impact on VS STM was nonsignificant, indicating that VS STM was not a significant mediator of the relation.

Central Executive (CE) Mediating ADHD Applied Problem Solving Deficits

A diagnosis of ADHD was associated with significantly poorer CE ability (Cohen's *d* = -1.25; Figure 1c, path a), and CE ability was related significantly to Applied Problem Solving abilities independent of Diagnostic Status (β = 0.41; Figure 1c, path b). Examination of the mediation pathway (Figure 1c, path ab) revealed that Diagnostic Status exerted a significant, moderate magnitude indirect effect on Applied Problem Solving abilities (Cohen's *d* = -0.52; 95% CI [-0.96, -0.21]) through its impact on CE, accounting for 60% of the relation between Diagnostic Status and Applied Problem Solving ability (Effect Ratio = .60). The relation between Diagnostic Status and Applied Problem Solving was not significant after accounting for CE (*d* = -0.36, 95% CI [-0.88, 0.17]), indicating that CE was a full mediator of ADHD-related applied problem solving differences.

Math Calculation Mediating ADHD Applied Problem Solving Deficits

A diagnosis of ADHD was associated with significantly poorer Math Calculation ability (Cohen's *d* = -0.75; Figure 1d, path a), and Math Calculation was related significantly to Applied Problem Solving abilities independent of Diagnostic Status (β = 0.69; Figure 1d, path b). Examination of the mediation pathway (Figure 1d, path ab) revealed that Diagnostic Status exerted a significant, moderate magnitude indirect effect on Applied Problem Solving (Cohen's *d* = -0.52; 95% CI [-0.87, -0.23]) through its impact on Math Calculation ability and accounted for 60% of the relation between Diagnostic Status and Applied Problem Solving (Effect Ratio = .60). The relation between Diagnostic Status and Applied Problem Solving remained significant after accounting for Math Calculation (*d* = -0.36, 95% CI [-0.69, -0.02]), indicating that Math Calculation ability was a partial mediator of ADHD-related Applied Problem Solving difficulties.

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 multiple 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 (e.g., attentional control, inhibition of irrelevant information, retrieval of mathematical factual knowledge and problem solving algorithms from long-term memory, and updating, reordering, and manipulation of the information used while completing mathematical calculations) are upstream of math calculation processes, rather than vice versa.

The total effect of Diagnostic Status on Applied Problem Solving (*d* = -0.87; Figure 2, path c) was significantly attenuated when CE and Math Calculation were included as mediators (*d* = -0.19; Figure 2, path c'), such that the combined effect of all three mediating pathways accounted for 79% of the Diagnostic Status/Applied Problem Solving relation (Effect Ratio = .79) 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; Effect Ratio = .36; Figure 2, CE → Math Calculation Indirect Effect) such that their joint influence explained 36% of ADHD-related Applied Problem Solving relation. 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; Effect Ratio = .24; 95% CI included 0.0; Figure 2, 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 = .20; 95% CI included 0.0; Figure 2, Math Calculation Indirect Effect). This finding indicates 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.

CHAPTER FOUR: CONCLUSION

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. Neither VS STM nor PH STM served as significant mediators for ADHD-related applied mathematic problem solving differences. The lack of significant PH STM mediation was unexpected based on extant literature. 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; Metcalf et al., 2016; Sarver et al., 2012; Swanson & Jerman, 2006; Swanson & Sachse-Lee, 2001). 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 the child to read applied problems based on (a) best-practice recommendations to minimize the influence of reading comprehension (Zentall & Ferkis, 1993) given the large magnitude relations between applied problem solving and reading comprehension (Swanson & 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, Rapport, Raiker, Orban, & Eckrich, 2016).

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 involvement of the two processes in applied problem solving (Zentall & Ferkis, 1993), and warranted examining whether they would remain independent influences or are more accurately portrayed as interacting processes (Swanson & Fung, 2016). The ensuing serial mediation model revealed 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 (i.e., inhibition of irrelevant information from entering/competing with temporarily stored information), reordering/sequencing, and a moderate interplay with long-term memory to activate knowledge of numbers and letters (Simmons et al., 2012; Swanson & Alloway, 2012; Swanson & 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 & 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 & Fung, 2016); however, the lack of PH STM involvement in ADHD-related applied problem solving deficits 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, Rapport, Bolden, Sarver, & Raiker, 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, Huang-Pollock, & Nigg, 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 suggesting that the default mode network hypothesis is insufficient for fully explaining the study's findings. 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 or interactive contributions to ADHD-related applied problem solving deficits but such distinctions warrant scrutiny.

Several caveats merit consideration despite methodological (e.g., stringent, multi-method/multi-informant diagnostic procedures; multiple tasks to estimate WM constructs) and statistical (e.g., bootstrapped mediation) refinements. Due to the well-documented gender differences related to ADHD symptom presentation (Williamson & 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, 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—e.g., neurodevelopmental disabilities (Luna et al., 2002; Swanson & Sachse-Lee, 2001), depression (Harvey et al., 2004), anxiety (Tannock, Ickowicz, & Schachar, 1995)—to elucidate shared and unique cognitive contributors of applied problem solving difficulties.

Complementary neuroimaging studies are also 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 collectively 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 deficits identified in the current study have several clinical implications. The large magnitude applied problem solving deficits 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, intensive behavioral treatments, or their combination; Jensen et al., 2007, 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, and reviews indicate that studies training PH/VS STM abilities result in moderate magnitude improvements on similar tasks (i.e., near transfer effects) but are unsuccessful in improving academic achievement (i.e., far transfer effects). The latter finding is anticipated given the lack of significant PH and VS STM mediation in the present and past studies (Friedman et al., 2016). However, few of the extant cognitive training programs target deficient CE processes (cf. Rapport et al., 2013, for a review). The results of the current investigation indicate that future interventions should include adaptive training modules that jointly train CE and calculation processes consistent with their interactive nature. Given recent evidence indicating that the pattern of neurocognitive deficits varies greatly among children with ADHD (Epstein et al., 2011; Willcutt, Doyle, Nigg, Faraone, & Pennington, 2005), future cognitive training programs may prove more successful by adopting a personalized medicine approach that targets intraindividually identified cognitive and academic strengths and weaknesses.

APPENDIX A:
TABLES AND FIGURES

Table 1 Sample and Demographic Variables

Variable	ADHD		Typically Developing			
	$\bar{X}$	*SD*	$\bar{X}$	*SD*	*t*	Cohen's *d*
Age	9.45	1.18	9.96	1.34	1.68	-0.41
FSIQ	104.33	9.92	110.42	11.98	2.31*	-0.55
$FSIQ_{res}$	-0.03	0.90	0.03	1.09	0.24	-0.06
SES	48.67	10.60	52.82	9.69	1.69	-0.41
CBCL AD/HD Problems	72.56	6.91	53.09	6.49	-12.04***	2.90
TRF AD/HD Problems	67.94	7.76	51.24	10.27	-7.66***	1.83
CSI-P: ADHD, Combined	76.50	9.42	47.91	10.24	-12.08***	2.91
CSI-T: ADHD, Combined	69.14	9.37	47.42	7.02	-10.82***	2.62
Applied Problem Solving	101.11	12.92	114.06	13.93	4.01***	-0.96
Math Calculation	94.94	12.48	105.15	12.88	3.34***	-0.81
Phonological STM Factor Score	-0.41	1.06	0.45	0.70	3.95***	-0.96
Visuospatial STM Factor Score	-0.31	0.97	0.34	0.93	2.84**	-0.68
Central Executive Factor Score	-0.60	0.88	0.65	0.67	6.62***	-1.60

Note: 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. * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$.

Table 2 First-order correlations

Table 2. First-order correlations

		1	2	3	4	5
1.	Diagnostic status (TD = 0, ADHD = 1)					
2.	Central Executive	-.63* (-.74, -.50)				
3.	PH STM	-.43* (-.61, -.24)	.63* (.49, .74)			
4.	VS STM	-.33* (-.53, -.11)	.60* (.44, .75)	-.23* (-.43, -.003)		
5.	Math Calculation	-.38* (-.56, -.17)	.47* (.22, .73)	.31* (.11, .49)	.28* (.01, .51)	
6.	Applied Problem Solving	-.44* (-.63, -.24)	.53* (.35, .67)	.32* (.07, .54)	.34* (.08, .56)	.76* (.63, .84)

Note: ADHD = attention-deficit/hyperactivity disorder; PH STM = phonological short-term memory; TD = typically developing; VS STM= visuospatial short-term memory. Correlations reflect bias corrected, bootstrapped Pearson's Correlation coefficients with 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 & Bolger, 2002).

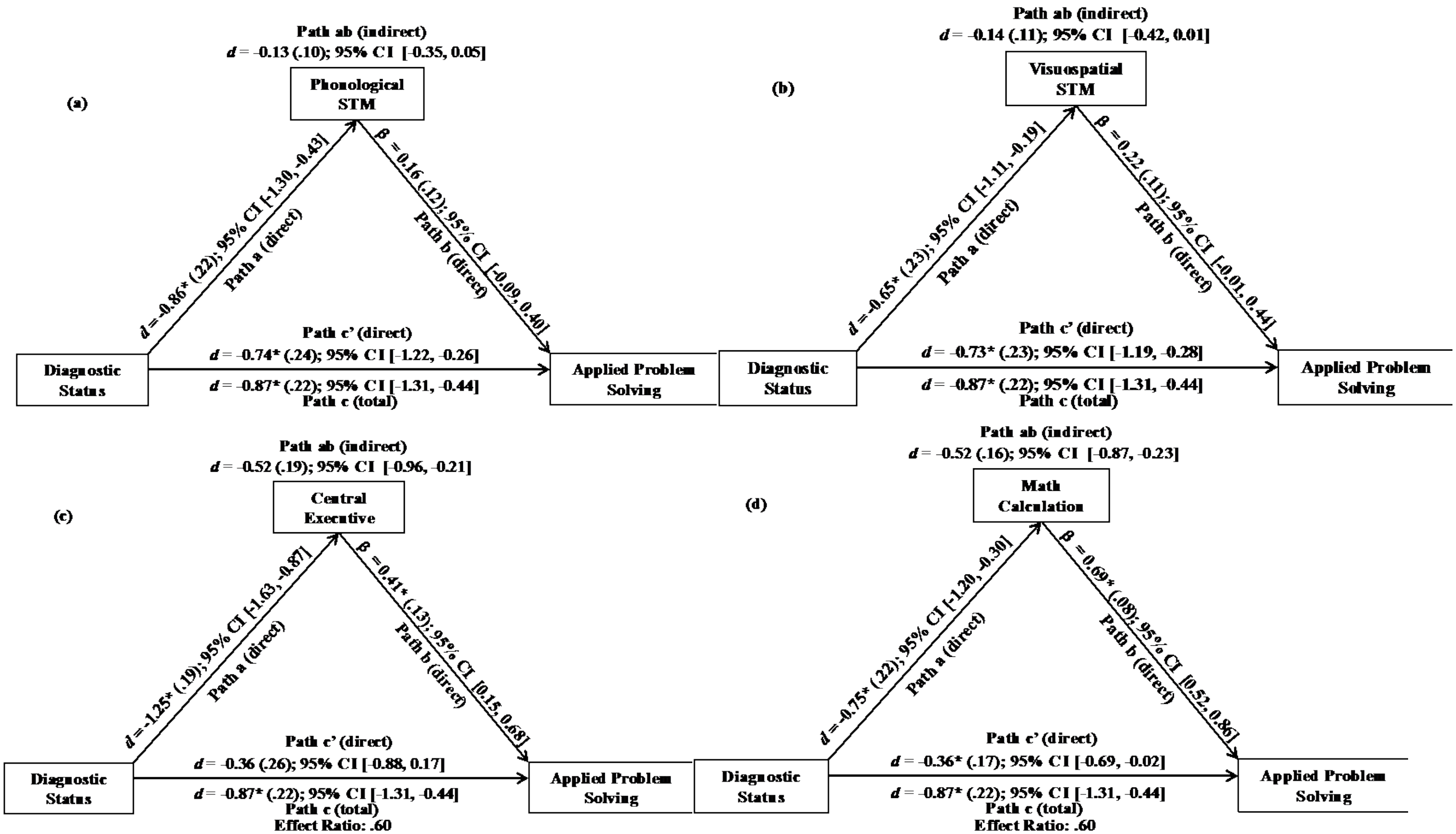

Figure 1: Simple Mediation Models

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 & Bolger, 2002); values for path b reflect *B*-weights due to the use of two continuous variables in the calculation of the direct effect.

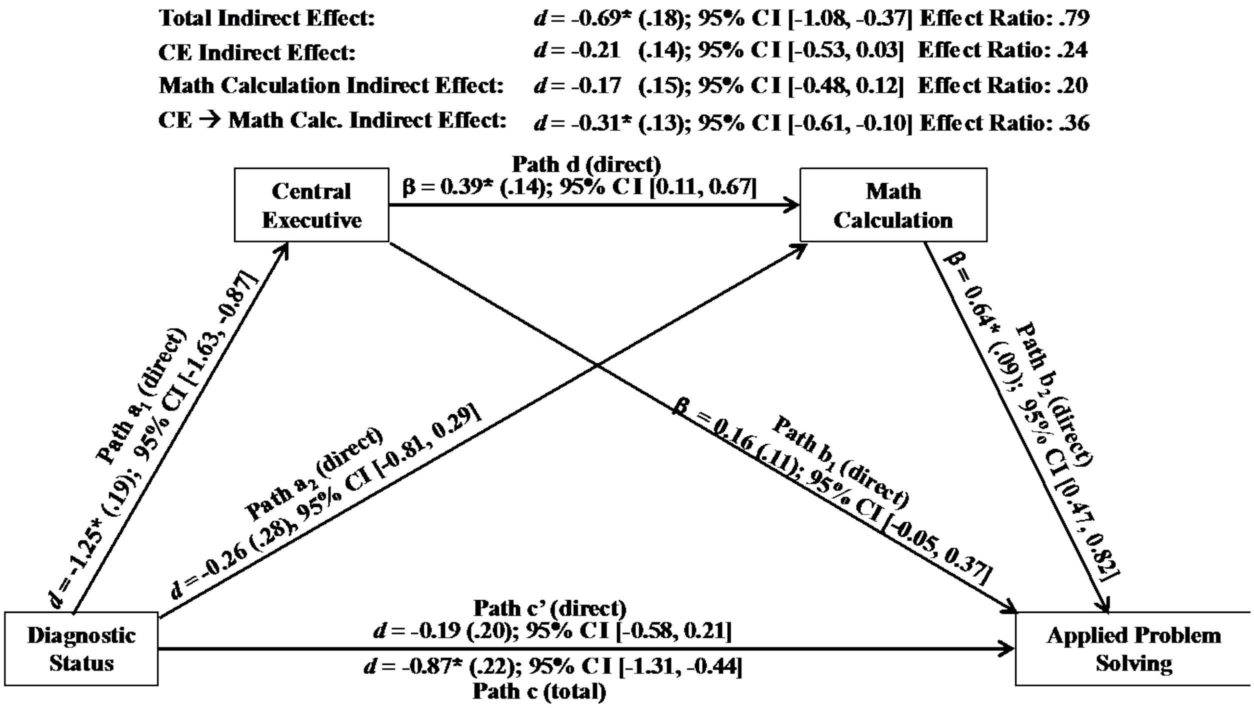

Figure 2: Serial Mediation Models.

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 & 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.

APPENDIX B:
IRB APPROVAL LETTER

University of Central Florida

University of Central Florida Institutional Review Board
Office of Research & Commercialization
12201 Research Parkway, Suite 501
Orlando, Florida 32826-3246
Telephone: 407-823-2901 or 407-882-2276
www.research.ucf.edu/compliance/irb.html

Approval of Human Research

From: **UCF Institutional Review Board #1**
FWA00000351, IRB00001138

To: **Mark D. Rapport, Ph.D.** and Co-PI: **Corey J. Bohil**

Date: **January 13, 2017**

Dear Researcher:

On 01/13/2017 the IRB approved the following human participant research until 01/12/2018 inclusive:

Type of Review:	Submission Response for IRB Continuing Review Application Form
Project Title:	An fNIRS Investigation of Neural Biomarkers Underlying Deficient Executive? Function (EF) Abilities in Children with ADHD
Investigator:	Mark D. Rapport, Ph.D.
IRB Number:	SBE-15-11040

The scientific merit of the research was considered during the IRB review. The Continuing Review Application must be submitted 30days prior to the expiration date for studies that were previously expedited, and 60 days prior to the expiration date for research that was previously reviewed at a convened meeting. Do not make changes to the study (i.e., protocol, methodology, consent form, personnel, site, etc.) before obtaining IRB approval. A Modification Form **cannot** be used to extend the approval period of a study. All forms may be completed and submitted online at https://iris.research.ucf.edu .

If continuing review approval is not granted before the expiration date of 01/12/2018, approval of this research expires on that date. When you have completed your research, please submit a Study Closure request in iRIS so that IRB records will be accurate.

Use of the approved, stamped consent document(s) is required. The new form supersedes all previous versions, which are now invalid for further use. Only approved investigators (or other approved key study personnel) may solicit consent for research participation. Participants or their representatives must receive a copy of the consent form(s).

All data, including signed consent forms if applicable, must be retained and secured per protocol for a minimum of five years (six if HIPAA applies) past the completion of this research. Any links to the identification of participants should be maintained and secured per protocol. Additional requirements may be imposed by your funding agency, your department, or other entities. Access to data is limited to authorized individuals listed as key study personnel.

In the conduct of this research, you are responsible to follow the requirements of the Investigator Manual.

On behalf of Sophia Dziegielewski, Ph.D., L.C.S.W., UCF IRB Chair, this letter is signed by:

Kanielle Chap

Signature applied by Kamille Chaparro on 01/13/2017 03:22:11 PM EST

IRB Coordinator

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