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ADHD and Core Foundational Learning: Working Memory's Contribution to Reading Comprehension and Applied Math Problem-Solving Abilities

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Decades of empirical research and myriad qualitative and meta-analytic reviews consistently identify academic achievement deficiencies among children with ADHD—particularly within the domains of reading comprehension and applied math problem solving. Children with ADHD are diagnosed with learning disabilities in reading and math at disproportionately higher rates relative to their peers, and often score in the bottom quartile on standardized tests of reading and math (DuPaul, Morgan, Farkas, Hillemeier, & Maczuga, 2016; Frazier, Youngstrom, Glutting, & Watkins, 2007). These findings are of particular concern given that early reading and math difficulties portend later academic deficits, lower high school and college graduation rates, higher rates of criminal and delinquent behavior, lower socioeconomic status, and poorer occupational functioning (Barkley, 2015).

An oft-cited theoretical model proposed to account for the linkage between ADHD and academic achievement deficits is the clinical core symptom model, whose key hypothesis is that ADHD core symptoms—particularly inattention—underlie academic achievement deficiencies by interfering with basic learning processes such as attending to, comprehending, and following classroom instructions (Breslau et al., 2009; Rabiner & Coie, 2000). A logical extrapolation of the model's central premise is that treatment-related remission of core symptoms (e.g., decreased inattention) should translate into improved learning and higher rates of academic achievement. Regrettably, multiyear clinical outcome studies have failed to demonstrate this expected transfer effect. For example, a majority of children who participated in the Multimodal Treatment Study of Children with ADHD (MTA) study and were assigned to one of its three gold standard treatment conditions (individually titrated psychostimulant medication, comprehensive behavioral intervention, or combined treatment)

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exhibited significant improvement in all three core ADHD symptom domains (inattention, hyperactivity, impulsivity), but failed to improve on any of the standardized educational achievement measures (DuPaul et al., 2016; Molina et al., 2009). These findings provide compelling evidence that treatments aimed at reducing core behavioral symptoms of ADHD are unlikely to benefit learning-related outcomes such as reading comprehension and math problem-solving abilities that are governed predominately by cognitive mechanisms and processes.

Prior to designing the studies described below, the University of Central Florida's (UCF) Children's Learning Clinic research team debated at length regarding which cognitive processes might prove to be the most promising contributors to ADHD–related reading comprehension and math problem-solving deficits. Our decision to focus on working memory (WM) was based on several factors: (a) an extensive literature review of studies demonstrating a moderate to strong involvement of WM in nearly all areas of core foundational learning, as well as educationally related activities such as attentional control, planning, organization, and multi-tasking; (b) extensive evidence that WM is highly heritable (Miyake et al., 2000) and shows strong developmental continuity from early childhood through adulthood (Huizinga, Dolan, & van der Molen, 2006; Park et al., 2002); and (c) the ability to examine the relative contribution of separable WM components (described below) to academic functioning.

Working memory (WM) is a limited-capacity, multi-component system responsible for temporarily storing and processing sensory information (Baddeley, 2007). The *working* component of WM, also known as the Central Executive (CE), is responsible for focusing attention, inhibiting irrelevant information from accessing focused attention, and updating, manipulating, and reordering information stored within two anatomically distinct subsidiary *memory* systems—the phonological (PH) and visuospatial (VS) short-term memory subsystems—which are responsible for the temporary storage and maintenance of verbal and non-verbal visual/spatial information, respectively.

The separability of the WM system is supported by decades of experimental, developmental, and factor analytic research as well as neuroanatomical studies indicating that WM components are localized in different cortical regions (Baddeley, 2007). Meta-analytic reviews consistently identify significant WM deficits in children with ADHD relative to their peers (Kasper, Alderson, & Hudec, 2012), and experimental investigations fractionating system components uniformly reveal large magnitude deficits in the upper-level *working* (CE) component and small to moderate magnitude deficits in the lower-level subsidiary *memory* stores (Rapport et al., 2008).

Reading comprehension and applied math problem solving involve multiple interacting WM processes (see Table 1; Swanson & Alloway, 2010). For example, when completing a math word problem, the PH short-term memory (STM) system temporarily stores the text, partial solutions, and mathematic rules accessed from long-term memory, while the VS STM temporarily stores non-verbal representation and organizes visual information (e.g., lining up the tens place correctly). The CE coordinates the exchange of information between the two stores while determining whether information within the stores is relevant, updates the stores with newer information, makes connections between learned math knowledge and the presented problem, maintains the overall goal of the word problem, and focuses attention while inhibiting irrelevant information from accessing the PH and VS stores.

Because WM plays key roles in reading comprehension and applied math problem solving—and children with ADHD have large deficits in WM—it stands to reason that ADHD–related reading comprehension and applied math difficulties may reflect underlying WM deficits. Only a handful of studies, however, have examined this hypothesis and found that phonological WM (i.e., using CE and PH STM jointly) contributes to ADHD–related reading com-

TABLE 1. Unique Roles of Working Memory Components in Reading Comprehension and Applied Math Problem Solving

The Role of Working Memory in Reading Comprehension		
Central Executive	**Phonological STM**	**Visuospatial STM**
• Determines relevance of read information	• Temporarily stores read information	• Maintains visual picture of read information
• Updates content of STM with newer information from the text		• Aids in text scanning
• Makes connections between what is being read and what is already known about the subject		
• Maintains the overall gist of what is read		
• Focuses attention on reading task		
• Inhibits irrelevant information from accessing STM		
The Role of Working Memory in Applied Math		
Central Executive	**Phonological STM**	**Visuospatial STM**
• Determines relevance of information presented in the problem	• Temporarily stores numbers and math rules	• Maintains mental picture of the math problem
• Updates content of STM with newer information or partial solutions generated	• Holds partial solutions while solving complex problems	• Aids in analysis of visual content (e.g., graphs)
• Accesses learned math concepts to be used in the presented problem	• Stores word problem text	• Assists in organizing visual and spatial information (e.g., lining up the tens place)
• Maintains the overall goal of the math problem		
• Focuses attention on the math problem		
• Inhibits irrelevant information from accessing STM		

Note. STM = short-term memory

prehension (Gremillion & Martel, 2012; Rogers, Hwang, Toplak, Weiss, & Tannock, 2011) and applied math difficulties (Gremillion & Martel, 2012; Kuhn, Ise, Raddatz, Schwenk, & Dobel, 2016). An additional investigation found that overall WM abilities (i.e., a combination of measures jointly assessing PH STM, VS STM, and CE) predict later applied math problem solving for those with high ADHD symptomatology (Rennie, Beebe-Frankenberger, & Swanson, 2014). No study to date, however, has dissociated the three WM components to determine their unique contributions to the difficulties children with ADHD experience in reading comprehension and applied math. Understanding the implicated WM subsystems is critical for identifying potential treatment targets for ADHD–related reading comprehension and applied math deficits.

An alternative explanation for ADHD–related reading comprehension and applied math difficulties involves the basic reading and math skills that enable these complex processes. In reading comprehension, one of the more central processes is referred to as orthographic conversion, which involves converting the visual/spatial shapes that comprise letters and words into a verbal code. For example, without knowing how to read Mandarin Chinese, 注意 is interpreted visually as a series of lines, but knowing the orthographic code allows one to convert this into the word "attention" and thus is interpreted using the phonological system. In applied mathematics problem solving, this process is called calculation and involves knowledge and execution of math facts and operations. For example, when determining the total number of chairs within 6 rows that each contains 37 chairs, calculation involves solving the equation 6 x 37.

A more parsimonious explanation for ADHD–related reading comprehension and applied math difficulties, however, is that basic orthographic conversion and math calculation skills interact with WM. Better-developed calculation and orthographic abilities enable a greater proportion of WM resources to be allocated towards understanding complex word problems or extracting meaning from text while reading. No study to date, however, has dissociated the three WM components (e.g., the CE, PH STM, and VS STM) while also examining their unique and interactive roles with calculation and orthographic conversion. The UCF Children's Learning Clinic research team conducted a series of experiments (Friedman, Rapport, Orban, Eckrich, & Calub, 2018; Friedman, Rapport, Raiker, Orban, & Eckrich, 2017) to address these questions.

METHODS

Participants

Two groups of boys aged 8 to 12 participated in the studies: (a) children with ADHD–Combined Presentation (n = 31, 36; Friedman et al., 2017; 2018), and (b) typically developing children without a psychological disorder (n = 30, 33; Friedman et al., 2017; 2018). All parents and children gave informed consent/assent, and institutional review board approval was obtained prior to data collection. Diagnosis was based on best practice recommendations and included detailed developmental histories, parent and child Kiddie Schedule for Affective Disorders and Schizophrenia (KSADS) semi-structured interviews, and parent and teacher rating scales (for additional details, see Friedman et al., 2017; 2018).

Procedure

The WM tasks (described below) were administered as part of a larger battery that required the child's presence for approximately 3 hours per session across four consecutive sessions. The Kaufman Test of Educational Achievement (KTEA), 1st or 2nd edition, was administered during two separate sessions to minimize fatigue. All variables, with the exception of WM and the Orthographic Speed tasks, were age-corrected, standardized scores from the KTEA–I or –II.

Measures

Working Memory Tasks. The Rapport and colleagues' (2008) computerized phonological and visuospatial working memory tasks correctly classify children with versus without ADHD at similar rates as parent and teacher ADHD rating scales (Tarle et al., 2017), and predict hyperactivity (Rapport et al., 2009), attention (Kofler, Rapport, Bolden, Sarver, & Raiker, 2010), impulsivity (Raiker, Rapport, Kofler, & Sarver, 2012), and ADHD–related functional impairments (Kofler et al., 2011). Their psychometric properties are well established (Kofler et al., 2018; Sarver, Rapport, Kofler, Raiker, & Friedman, 2015). The PH and VS WM tasks measure the ability to mentally store, rehearse, and manipulate the serial order of verbal or spatial stimuli, respectively. Descriptions of the two tasks and their administration are detailed in Rapport and colleagues (2008). Regression techniques were used to isolate unique and shared variance among WM tasks to produce separate central executive (CE), phonological short-term memory (PH STM), and visuospatial short-term memory (VS STM) component variables.

Applied Problem-Solving Task. KTEA Mathematics Applications/Math Concepts and Applications standardized subtest scores were used to measure children's ability to apply learned mathematical concepts to real-world scenarios.

Math Calculation Task. KTEA Math Computation standardized subtest scores were used to measure children's ability to solve increasingly complex math operations.

Reading Comprehension Task. The KTEA Reading Comprehension standardized subtest scores were used to assess comprehension of the literal and inferential meaning of printed text and required children to read increasingly complex printed passages and answer visually presented questions.

Orthographic Conversion. A factor score reflecting an estimate of overall orthographic conversion ability was created using the Orthographic Conversion Speed Task and the KTEA Reading Decoding/Letter-Word Recognition subtest (for task descriptions, see Friedman et al., 2017). The Orthographic Conversion factor was derived via principal components and factor analysis to reflect the speed and accuracy by which children were able to orthographically convert printed text.

RESULTS

ADHD and Reading Comprehension Study

Four potential mediating variables—PH STM, VS STM, CE, and Orthographic Conversion—were examined initially via simple mediation models to determine whether they independently contributed to ADHD–related Reading Comprehension difficulties. Only the latter two emerged as significant partial mediators of the relation between Diagnostic Status and Reading Comprehension. A multiple serial mediation model involving both CE and Orthographic Conversion was used subsequently to determine whether (a) their independent contributions were sufficient to account for ADHD–related Reading Comprehension difficulties; or (b) their influence is better explicated as an interaction between the two cognitive processes. When modeled jointly, the collective influence of CE and Orthographic Conversion fully accounted for between-group differences in reading comprehension and explained 61% of the variance between diagnostic status and reading comprehension (see Figure 1).

ADHD and Applied Math Problem-Solving Study

Simple mediation models were also used in our math study to determine the extent to which PH STM, VS STM, CE, and Math Calculation ability contributed uniquely to ADHD–related Applied Math Problem-Solving difficulties. Similar to our reading study, both CE and Math Calculation significantly mediated the relation between Diagnostic Status and Applied Problem Solving. Neither PH STM nor VS STM served as significant mediators. When modeled together via serial mediation analysis, CE in tandem with Math Calculation ability fully mediated the relation and explained 79% of the variance in ADHD–related applied math problem-solving ability.

IMPLICATIONS OF OUR FINDINGS

Collectively, the results of the serial mediation models revealed that the CE and basic academic skills (e.g., orthographic conversion and calculation) jointly mediated ADHD–related reading comprehension and applied math problem-solving difficulties fully, and likely reflect one or more cascading progressions. Based on extant literature, the most parsimonious explanation for the serial mediator finding is that deficient CE processes in children with ADHD weaken successful orthographic conversion of printed text and calculation due to (a) insufficient maintenance of attentional focus towards academic tasks; (b) inadequate inhibition of irrelevant information from entering the PH STM store (i.e., interference control); (c) slowed retrieval of stored words/phonemes or mathematical knowledge from long-term memory; and/or (d) slowed or deficient updating of newly decoded text or calculated information. The unique and synergistic contributions of these processes likely place additional demands on available CE resources, which in turn limit their availability for extracting knowledge while reading text or solving complex calculations.

A majority of children with ADHD experience moderate to significant impairment in two of the most critical areas of foundational knowledge—reading comprehension and applied math

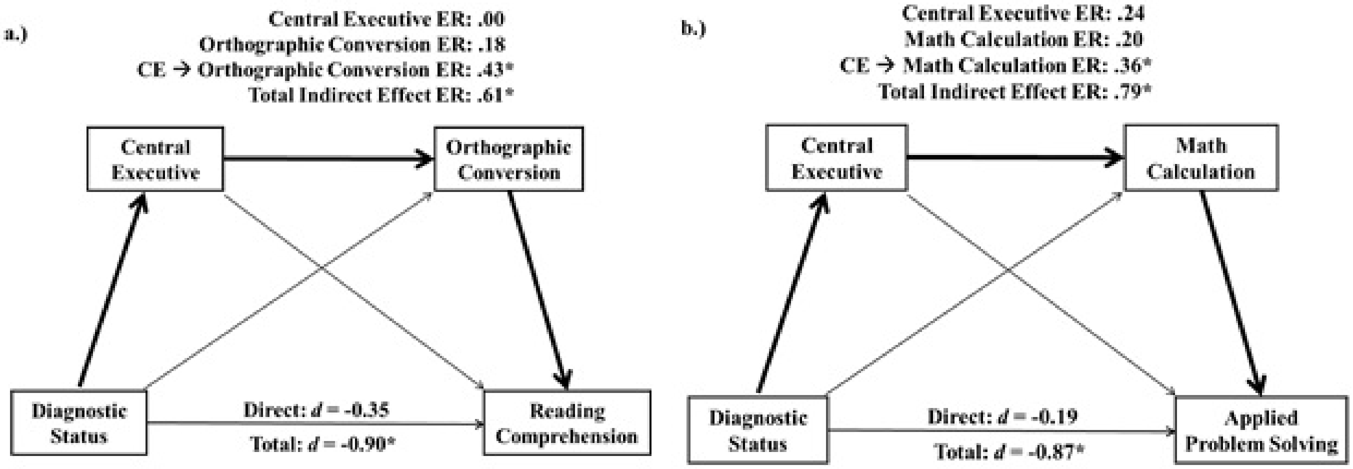

Figure 1. CE = Central Executive, ER = Effect Ratio. Schematics depicting the Effect Ratios and the total, direct, and indirect pathways for two serial mediation models involving the Central Executive and (a) Orthographic Conversion and (b) Math Calculation on ADHD–related Reading Comprehension (left) and Math Computation (right). *Effect size is significant based on 95% confidence intervals that do not include 0.0. 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.

problem-solving abilities. These findings are not unexpected given (a) the complex multi-system impairments and the 2 to 2.5 year developmental delays in networks that mediate domain general WM functioning (CE) and domain-specific subsidiary short-term memory processes (PH/VS STM) in a majority of children with ADHD (Rubia, 2018; Shaw et al., 2007); and (b) the critical importance of these mechanisms and processes to learning.

Given the overwhelming evidence and burgeoning neuroimaging literature documenting the significant cognitive delays and corresponding WM deficits in a majority of children with ADHD, we designed our two studies to explicate which WM–related processes, independently and/or in conjunction with basic academic processes, contribute to reading comprehension and applied math problem-solving deficits among children with ADHD. Although elucidation of the complexities underlying foundational knowledge was of interest, our primary objective was to inform the design of effective interventions for these children. For example, if one or both short-term memory stores were implicated, interventions could be designed to strengthen the primary processes that the STM stores handle (e.g., increasing and/or maintaining the amount of information required to comprehend read passages and solve math problems). Conversely, strengthening STM stores would result in marginal or no effect if CE deficits were the primary source of the children's reading comprehension and math problem-solving deficiencies.

Our results accentuate the importance of fractionating the multiple components of WM—neither PH STM nor VS STM served as contributing processes in children's reading comprehension and applied problem-solving abilities—only the shared influence between CE and orthographic conversation/calculation significantly explained ADHD–related reading comprehension and applied math deficits, respectively. These findings are important not only because they illuminate the etiological processes of the significant academic difficulties among children with ADHD, but also because they identify propitious targets for designing novel remedial interventions.

In recent years, WM training programs have garnered significant attention within the fields of psychology, psychiatry, and education. Introduced in the early 2000s, these programs are computer-based interventions designed to foster the growth of WM abilities by strengthening the underlying neural structures that support their function through repeated, adaptive training. Such programs are predicated on the concept of neuroplasticity—namely, that repeated practice will produce lasting benefits through the generation (neurogenesis) or rewiring (synaptogenesis) of existing neural pathways. Improved WM ability is expected to generalize to improvements on untrained targets (i.e., far transfer effects) such as academic achievement to the extent that they rely on WM. Recent meta-analytic reviews, however, uniformly reveal that extant WM training programs do not produce meaningful improvement in reading comprehension or applied math problem solving (Rapport, Orban, Kofler, & Friedman, 2013).

A highly plausible explanation for the lack of improvement in children's academic achievement after undergoing multi-week WM training is the misspecification of intervention targets by these programs. For example, 16 of the 17 studies identified in the Rapport and colleagues' (2013) meta-analytic review used training tasks that targeted short-term memory rather than upper level CE processes, whereas CE is the most significantly impaired WM component in children with ADHD (Rapport et al., 2008) and the only WM component found to mediate ADHD–related reading comprehension and applied math deficits in our studies. These findings highlight the need to include CE–strengthening tasks coupled with tasks that reinforce academically related processes such as orthographic conversion and calculation when designing future interventions. Conversely, strengthening PH/VS short-term storage/rehearsal subsystems functioning (which are anatomically distinct from the frontal/prefrontal CE) and expecting growth in the CE is akin to training your quads and biceps and expecting six-pack abs—it is highly unlikely that you will see the desired results.

It is important to note, however, that a one-size-fits-all intervention is unlikely to be an effective approach, given the significant variability in functional, academic, and neurocognitive deficits observed among children with ADHD. For example, a recent investigation found that nearly two-thirds of children with ADHD have deficits in WM, while 35% of children with ADHD experience multiple neurocognitive deficiencies (Kofler et al., 2017). These findings suggest that varying neurocognitive profile deficits among children with ADHD are the norm rather than the exception, and indicate that cognitive training interventions will need to be personalized based on inter-individually identified strengths and weaknesses.

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Sluggish Cognitive Tempo and Temporal Processing: An Exploratory Examination of Association Using a Novel Measure

Anne E. Sorrell and Will H. Canu, Ph.D.

Arguably first noted by Lahey, Schaughency, Strauss, and Frame (1984), the behavioral symptoms of sluggish cognitive tempo (SCT) include feeling sleepy or lethargic, having a tendency to daydream excessively, having trouble staying awake and alert, staring a lot, feeling mentally "foggy" or confused, seeming slow-moving or sluggish, and appearing to process information slowly (Barkley, 2014). Though these symptoms appear similar to those of the attention-deficit/hyperactivity disorder predominantly inattentive presentation (ADHD-IA), converging findings suggest that SCT is indeed empirically distinct from ADHD-IA and perhaps should be considered as a separate disorder of attention (Barkley, 2014; Becker & McBurnett, 2013; Becker et al., 2016). Several recent papers (e.g., Becker, Langberg, Luebbe, Dvorsky, & Flannery, 2014; Lee, Burns, Snell, & McBurnett, 2014; McBurnett et al., 2014; Willcutt et al., 2014) have shown SCT to be internally consistent and to represent a distinct latent factor from ADHD-IA. Other papers (Becker et al., 2013; Carlson & Mann, 2002; Lee, Burns, Beauchaine, & Becker, 2016) have found that those with SCT endorse more internalizing symptoms, such as anxiety and depression, as compared to peers with ADHD or oppositional defiant disorder, who are more likely to exhibit comorbid externalizing behaviors. Further work supports the hypothesis that SCT is generally associated with psychological dysfunction (Becker et al., 2014; Khadka, Burns, & Becker, 2015), including emotion dysregulation (Flannery, Becker, & Luebbe, 2016; Jarrett, Rapport, Rondon, & Becker, 2017), poor self-organization (Barkley, 2012), adjustment problems in social situations, school, and work (Flannery, Luebbe, & Becker, 2017), lower quality of life (Combs, Canu, Broman-Fulks, & Nieman, 2014), and higher subjective stress (Combs, Canu, Broman-Fulks, Rocheleau, & Nieman, 2015), independent of ADHD.

While the evidence that SCT is a bona fide psychological construct and one that is associated with significant impairment is thereby fairly robust, the cognitive basis of SCT is less well established, to date. Only one published study to date has examined neuroanatomical differences in individuals with elevated SCT symptoms. Fassbender, Krafft, & Schweitzer (2015) utilized functional magnetic resonance imaging to investigate the brain functioning of 29 adolescents with ADHD who did and did not have elevated SCT symptoms, based on parental ratings. Most notably, their results revealed that individuals with elevated SCT symptoms showed hypoactivity in the superior parietal lobe, suggesting impairment in the ability to reorient attention. This finding remained even when controlling for ADHD-IA. Though more neuroimaging research of SCT populations is clearly needed, the results from this study, again, support the idea that SCT and ADHD-IA brain functioning symptom profiles differ.

Of the many constructs that warrant further research regarding SCT's underpinnings, executive functioning (EF) abilities may be the most relevant. EF is generally conceptualized as higher order cognitive abilities that facilitate goal-directed behavior and self-control (Geurts, Verte, Oosterlaan, Roeyers, & Sergeant, 2004). This encompasses skills such as behavioral regulation, working memory, organizational skills, self-monitoring, planning and imple-