
Electronic Theses and Dissertations, 2004-2019

2014

Phonological Working Memory Deficits in ADHD Revisited: The Role of Lower-Level Information Processing Deficits in Impaired Working Memory Performance

Joseph Raiker
University of Central Florida



Part of the [Clinical Psychology Commons](#)

Find similar works at: <https://stars.library.ucf.edu/etd>

University of Central Florida Libraries <http://library.ucf.edu>

This Doctoral Dissertation (Open Access) is brought to you for free and open access by STARS. It has been accepted for inclusion in Electronic Theses and Dissertations, 2004-2019 by an authorized administrator of STARS. For more information, please contact STARS@ucf.edu.

STARS Citation

Raiker, Joseph, "Phonological Working Memory Deficits in ADHD Revisited: The Role of Lower-Level Information Processing Deficits in Impaired Working Memory Performance" (2014). *Electronic Theses and Dissertations, 2004-2019*. 1296.

<https://stars.library.ucf.edu/etd/1296>



PHONOLOGICAL WORKING MEMORY DEFICITS IN ADHD REVISITED: THE
ROLE OF LOWER-LEVEL INFORMATION PROCESSING DEFICITS IN IMPAIRED
WORKING MEMORY PERFORMANCE

by

JOSEPH S. RAIKER

B.S. University of Central Florida, 2007

M.S. University of Central Florida, 2011

A dissertation submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy
in the Department of Psychology
in the College of Sciences
at the University of Central Florida
Orlando, Florida, USA

Summer Term
2014

Major Professor: Mark D. Rapport

© 2014 Joseph S. Raiker

ABSTRACT

Working memory deficits in children with ADHD are well established; however, insufficient evidence exists concerning the degree to which lower-level cognitive processes contribute to these deficits. The current study dissociates lower level information processing abilities (i.e., visual registration, orthographic conversion, and response output) in children with ADHD and typically developing children and examines the unique contribution of these processes to their phonological working memory performance. Thirty-four boys between 8 and 12 years of age (20 ADHD, 14 typically developing) were administered novel information processing and phonological working memory tasks. Between-group differences were examined and bootstrap mediation analysis was used to evaluate the mediating effect of information processing deficits on phonological working memory performance. Results revealed moderate to large magnitude deficits in visual registration and encoding, orthographic to phonological conversion, and phonological working memory in children with ADHD. Subsequent mediation analyses, however, revealed that visual registration/encoding alone mediated the diagnostic group status/phonological working memory relationship and accounted for approximately 32% of the variance in children's phonological working memory performance. Diagnostic and treatment implications for understanding the complex interplay among multiple cognitive deficits in children with ADHD are discussed.

To my beautiful wife who supported me throughout this process. Without you, this would not have been possible.

ACKNOWLEDGMENTS

I would like to acknowledge my dissertation chair, Dr. Mark D. Rapport, for his unconditional support of me throughout my graduate training. You taught me how to work hard and play hard and ignited my passion for academic research. I thank God that I have had the opportunity to train under you and hope that I am able to provide the same level of mentorship to my students.

I would like to also acknowledge those members comprising my committee including Dr. Deborah C. Beidel, Dr. Mustapha Mouloua, and Dr. Eleazar “Trey” Vasquez. Your patience and flexibility were integral to my successful completion of this project. Additionally, your feedback at each level of completion and clear interest in this topic strengthened my enthusiasm and passion for this line of research. You each have inspired me to set out to accomplish a fraction of what you have accomplished throughout your careers.

Finally, I would like to thank my family. This extends beyond my immediate family and consists of my spiritual family, lab family, program family, and internship family. Each of you have influenced me positively in one way or another and were instrumental in shaping my success.

TABLE OF CONTENTS

LIST OF FIGURES	viii
LIST OF TABLES	ix
LIST OF ACRONOYMS	x
CHAPTER 1: INTRODUCTION	1
CHAPTER 2: METHODOLOGY	9
Participants.....	9
Group Assignment	9
Measures	11
Phonological Working Memory Tasks	11
Information Processing Tasks.....	12
Picture naming task.....	13
Picture reaction time (RT) task.....	14
Motor speed task.....	15
Measured intelligence	16
Dependent Variables.....	16
Phonological working memory.....	16
Visual registration and encoding	16
Orthographic-to-phonological conversion	17
Response preparation and skeletomotor speed	17

Procedures.....	17
Analysis Overview.....	18
Mediation Analysis.....	19
CHAPTER 3: RESULTS.....	21
Preliminary Analysis.....	21
Tier I: Intercorrelations.....	21
Tier II: Mediation Analyses.....	22
Total effect.....	22
Skeletomotor speed mediating phonological working memory.....	22
Visual registration/encoding mediating phonological working memory.....	22
Orthographic-to-phonological conversion mediating phonological working memory	23
CHAPTER 4: DISCUSSION.....	30
APPENDIX: IRB APPROVAL LETTER.....	38
LIST OF REFERENCES.....	40

LIST OF FIGURES

- Figure 1. Adapted and expanded version of Baddeley’s (2007) phonological working memory subsystem and corresponding components of processing speed from stimulus onset to response output based on Jacobson et al. (2011). PH = Phonological. LTM = Long-term Memory. RT = Reaction time. STS = Short-term store. Reprinted and expanded with permission from the author..... 27
- Figure 2. Schematic illustrating the information processing subcomponents examined in the current study (middle column), the experimental tasks used to derive indices of each information processing subcomponent (left), and the statistical method for deriving reliable variance associated with each subcomponent (right). RT = reaction time. 28
- Figure 3. Schematic depicting (a) the effect sizes and B coefficients of the total, direct, and indirect pathways for the mediating effect of (b) visual registration and encoding and (c) orthographic-to-phonological conversion on phonological working memory. 29

LIST OF TABLES

Table 1. Sample and Demographic Variables.....	24
Table 2. Intercorrelations among variables.....	25
Table 3. Mediation analyses: Impact of diagnostic status (ADHD, TD) and information processing subcomponents on phonological working memory	26

LIST OF ACRONOYMS

ADHD	Attention-Deficit/Hyperactivity Disorder
CBCL	Child Behavior Checklist
CI	Confidence Interval
CLC	Children's Learning Clinic
CSI-P	Child Symptom Inventory – 4: Parent Checklist
CSI-T	Child Symptom Inventory – 4: Teacher Checklist
EF	Executive Function
ES	Effect Size
FSIQ	Full Scale Intelligence Quotient
K-SADS	Kiddie Schedule for Affective Disorders and Schizophrenia for School-Aged Children
LTM	Long-term Memory
MS	Milliseconds
OC	Orthographic Conversion
ODD	Oppositional Defiant Disorder
PH	Phonological
RT	Reaction Time
SD	Standard Deviation
SE	Standard Error
SES	Socioeconomic Status

STS	Short-term Store
TRF	Teacher Report Form
VR	Visual Registration
VS	Visuospatial
WISC	Wechsler Intelligence Scale for Children
WM	Working Memory

CHAPTER 1: INTRODUCTION

Current diagnostic conceptualizations of attention-deficit/hyperactivity disorder (ADHD) regard deficiencies in attention and excesses in gross motor/impulsive behavior as core features of the disorder (APA, 2013). These symptoms and their association with dysfunction in multiple areas of executive function are well documented (Barkley, 1997; Rapport, Alderson et al., 2008; Sonuga-Barke, Bitsakou, & Thompson, 2010; Willcutt, Doyle, Nigg, Faraone, & Pennington, 2005) and consistent with neuroanatomical evidence demonstrating delayed cortical maturation in brain regions associated with executive functioning in children with ADHD (Shaw et al., 2007). Executive functions (EF) refer to separable but interrelated cognitive abilities that involve frontal/prefrontal cortical areas and allow for the planning, regulation, execution, and inhibition of behavior (for a review, see Willcutt et al., 2005).

Working memory (WM) has emerged as a particularly promising executive function for understanding a wide array of ADHD symptoms and related disabilities based on meta-analytic (Kasper, Alderson, & Hudec, 2012; Martinussen, Hayden, Hogg-Johnson, & Tannock, 2005; Willcutt et al., 2005) and summative reviews (Sergeant, Geurts, & Oosterlaan, 2002) as well as empirical investigations (Holmes et al., 2010; Rapport, Alderson et al., 2008). Working memory is a limited capacity system responsible for the temporary storage, rehearsal, and manipulation of internally held information for use in guiding behavior. Extensive evidence reveals two distinct working memory subsystems—phonological (PH) and visuospatial (VS)—that are responsible for the temporary storage and rehearsal of modality specific information and whose functions are coordinated by a domain-general attentional controller termed the central executive (Baddeley,

2007; 2012). The central executive and its associated processes reflect the *working* components of working memory and are responsible for the mental processing of internally held information (cf. Wager & Smith, 2003).

Phonological working memory and its interrelated processes warrant particular empirical scrutiny due to the phonological subsystem's involvement in and contribution to the development of academic related abilities such as sentence repetition (Alloway, Gathercole, Willis, & Adams, 2004), sentence comprehension (Montgomery, 1995), word identification/recognition (Swanson & Howell, 2001), and reading comprehension (Cain, Oakhill, & Bryant, 2004). Phonological working memory also predicts children's aptitude in reading (Alloway & Alloway, 2010; Durand, Hulme, Larkin, & Snowling, 2005), mathematics (Alloway & Alloway, 2010; Gathercole, Alloway, Willis, & Adams, 2006; Meyer, Salimpoor, Wu, Geary, & Menon, 2010; Swanson & Kim, 2007), and science (Gathercole, Pickering, Knight, & Stegmann, 2004). Phonological working memory deficits in children with ADHD are well established based on meta-analytic reviews (Frazier, Demaree, & Youngstrom, 2004; Kasper et al., 2012; Martinussen et al., 2005) and empirical investigations (Holmes et al., 2010; Rapport, Alderson et al., 2008), and take on additional importance as robust predictors of long-term academic aptitude (Gathercole, Brown, & Pickering, 2003; Hinshaw, 1992; Rapport, Scanlan, & Denney, 1999) and comorbid reading disabilities in this population (e.g., Martinussen & Tannock, 2006; Semrud-Clikeman et al., 1992; Willcutt & Pennington, 2000).

Cognitive training programs developed to remediate phonological WM deficits have proliferated in recent years (cf. Shipstead, Redick, & Engle, 2012) due, in part, to the reliable

findings that current ADHD medications have minimal impact on cortical regions associated with working memory and minimally impact working memory performance for these children (Rubia et al., 2013). The goal of these programs is to strengthen children's working memory abilities with the expectation that training will generalize to improvements on other tasks that require these abilities (near transfer effects), and more importantly, to untrained skills and abilities that require the trained brain functions for successful execution such as reading and mathematic aptitude and non-verbal reasoning (far transfer effects). Findings from a recent meta-analytic review (Rapport, Orban, Kofler, & Friedman, 2013) indicate that these programs show initial promise and are associated with moderate magnitude improvements in short-term memory (near transfer $ES = .63$) that approximate the short-term memory deficits exhibited by children with ADHD. In contrast, small magnitude improvements were documented for far transfer measures ($ES = .36$); however, these effects were limited to unblinded behavioral ratings and were no longer significant after accounting for illusory bias effects.

The promising albeit limited success of extant working memory training programs for children with ADHD may reflect at least two potential shortcomings inherent to their design. The programs place marginal or no emphasis on training higher-order executive functions such as central executive-mediated updating, dual tasking, and serial reordering of information held in the phonological and visuospatial storage/rehearsal subsystems (Chacko et al., 2013). This oversight is critical given evidence that these abilities may be the most impaired and show the strongest continuity with ADHD behavioral and functional impairments based on meta-analytic reviews (e.g., Kasper et al., 2012; Martinussen et al., 2005) and controlled experimental

investigations (Rappaport, Alderson et al., 2008). A second potentially limiting and overlooked factor is that phonological working memory deficits in ADHD may occur secondary to deficits in more basic cognitive processes (Karalunas & Huang-Pollock, 2013) involved in the registration, encoding, and conversion of visual stimuli to phonological code (i.e., orthographic to phonological conversion). Examination of these information processing subcomponents is critical given their fundamental role in preparing information for use by the articulatory-based phonological subsystem (Baddeley, 2007) as a prerequisite for higher-order executive processing related to reading competency (Jacobson et al., 2011; McGrath et al., 2011). For example, a recent study by Jacobson and colleagues (2011) concluded that deficiencies in response preparation, but not basic motor speed (Figure 1), predicted phonological working memory and oral reading fluency in children with ADHD. No study to date, however, has further fractionated response preparation into its component processes of visual encoding, mental transformations and associations (e.g., orthographic to phonological conversion), and response selection/preparation (Jacobson et al., 2011). In addition, despite their elegant design, Jacobson and colleagues (2011) were unable to control for potential between-group differences in basic visual perception and registration of stimuli, and were limited to WISC-IV Coding and Symbol Search subtests as indices of information processing. Importantly, both WISC-IV subtests use abstract stimuli that preclude examination of orthographic conversion of visually-presented stimuli into phonological code – a process antecedent to gaining access to the phonological short-term store and inherent to higher-order abilities such as reading fluency and comprehension (Alderson et al., 2014).

Interestingly, Jacobson et al. (2011) reported no deficiencies in graphomotor speed for children with ADHD relative to typically developing children – a finding that appears to contradict meta-analytic findings based on over 300 ADHD studies demonstrating slower and more variable basic motor speed across a wide range of computerized laboratory-based tasks (Kofler et al., 2013). This discrepancy may reflect important methodological differences between Jacobson et al. (2011) and previous studies. For example, both information processing tasks in the Jacobson et al. (2011) study relied on graphomotor speed, whereas the tasks reviewed in the Kofler et al. (2013) meta-analysis rely primarily on skeletomotor speed to index processing speed in children with ADHD relative to typically developing children. Skeletomotor speed is conventionally considered a more precise measure of motor output due to the increased variety of processes involved in graphomotor output (e.g., pencil grip, eye-hand coordination; Cornhill & Case-Smith, 1996). A second methodological difference concerns the measurement of total processing time required by a task. The WISC-IV tasks used by Jacobson et al. (2011) provide a single score taken at the conclusion of a task to estimate response output, whereas computerized tasks record response output continuously for each trial with millisecond precision. Frequent, repeated sampling over time is likely to provide a more accurate measure of children's rate of information processing and allow fractionation of multiple components of information processing through experimental manipulation of key task parameters (Figure 2).

To date, no ADHD study has disassociated early visual perception and encoding from lower-level mental transformation (e.g., orthographic to phonological conversion) and basic skeletomotor speed to examine the role of these information processing subcomponents in

ADHD phonological working memory deficits. Early investigations of visual encoding using a stimulus degradation paradigm, however, surmised that this early stage of information processing was likely intact in ADHD (Sergeant & Scholten, 1985), whereas a more recent investigation suggests that children with ADHD require significantly more visual information and longer durations to correctly identify a visual stimuli relative to typically developing children (Ballesteros, Reales, & García, 2007). Neither study controlled for the complex processing demands involved in their tasks (e.g., accessing long-term memory to convert visual stimuli to phonological code) and thus provide limited information regarding the extent to which slowed visual registration processes in children with ADHD may impact later processing stages (e.g., orthographic to phonological conversion, phonological/storage rehearsal). The degree to which each of these component processes are affected has potentially important implications for understanding phonological working memory deficits in ADHD, particularly as they relate to the attainment of phonologically-mediated academic abilities such as reading comprehension. For example, slowed registration and encoding of visual information (e.g., letter or words) would delay the rate at which this orthographic information could be converted into phonological code, creating a potential bottleneck of information attempting to access the phonological short-term store. Reduced storage capacity, in turn, places clear limits on phonological working memory processing and is associated with deficient learning across a wide range of academic areas including reading (Durand et al., 2005), math (Alloway & Alloway, 2010), and science (Gathercole et al., 2004).

Examination of orthographic to phonological conversion processes (Figure 1) is also necessary as deficits in these processes in the absence of visual registration or early encoding deficits could also result in the ‘bottleneck’ described above. Findings from ADHD studies examining this process via rapid naming tasks involving letters and numbers are mixed (Alderson et al., 2014; Carte, Nigg, & Hinshaw, 1996; Semrud-Clikeman, Guy, Griffin, & Hynd, 2000; Tannock, Martinussen, & Frijters, 2000), whereas rapid naming tasks with reading-unrelated stimuli (e.g., colors, familiar objects) appear to more reliably detect slowed orthographic to phonological conversion processes in ADHD relative to typically developing groups (Banaschewski et al., 2006; Carte et al., 1996; Lawrence et al., 2004; Rucklidge & Tannock, 2002; Semrud-Clikeman, et al., 2000; Shanahan et al., 2006; Tannock et al., 2000; Wodka et al., 2008) with some exceptions (Li et al., 2009; Wodka et al., 2008). One potential shortfall of rapid letter/number naming tasks is their dependence on additional, reading-specific skills known to be affected in ADHD (Tannock et al., 2000), suggesting that reading-unrelated stimuli may be preferable in ADHD studies examining orthographic-to-phonological conversion processes. However, rapid naming tasks in isolation preclude fractionation of the multiple information processing subcomponents detailed above, and none of the reviewed studies controlled for critical visual input and response output processes. In addition, only three ADHD studies to date have examined the association between deficits in lower-level information processing and higher-order working memory deficits (Alderson et al., 2014; Jacobson et al., 2011; Karalunas & Huang-Pollock, 2013), and none of these studies were able to disassociate the

unique role of visual registration and encoding, orthographic-to-phonological conversion, and response preparation and output processes.

The current study addresses these limitations and examines the extent to which lower-level information processing components are (a) impaired in children with ADHD, and (b) involved in the large magnitude phonological working memory deficits previously identified in this population (Kasper et al., 2012). A series of counterbalanced tasks, each administered on two occasions 1-week apart, were used to isolate reliable variance associated with the visual registration and encoding, orthographic-to-phonological conversion, and response preparation and skeletomotor output phases of information processing, and evaluate the extent to which impairments in these lower-level processes are implicated in the phonological working memory deficits associated with ADHD. Consistent with previous studies (Karalunas & Huang-Pollock, 2013; Jacobson et al., 2011), we hypothesized that children with ADHD would demonstrate deficiencies in one or more of these information processing subcomponents; more specific predictions were not offered given the paucity of research dissociating these lower-level processes. In addition, we expected that identified impairments in one or more of these information processing stages would contribute significantly to ADHD children's phonological working memory deficits (i.e., would mediate the relation between ADHD status and phonological working memory performance) based on the rationale described above.

CHAPTER 2: METHODOLOGY

Participants

The sample comprised 34 boys aged 8 to 12 years, recruited by or referred to a children's learning clinic (CLC) through community resources (e.g., referrals from pediatricians, community mental health clinics, school system personnel, and self-referral or resulting from web-based searches). 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 children participated in the study: children with ADHD, and typically developing children without a psychological disorder. Children 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 less than 85 were excluded from the study.

Group Assignment

All children and their parents participated in a detailed, semi-structured clinical interview using 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).

Twenty children meeting the following criteria were included in the ADHD-Combined Type group: (1) an independent diagnosis by the CLC's directing clinical psychologist using DSM-V criteria for ADHD-Combined Type based on K-SADS interview with parent and child which assesses symptom presence and severity across home and school settings; (2) parent ratings of at least 2 SDs 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, 2004); and (3) teacher ratings of at least 2 SDs 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. Their psychometric properties are well established (Rapport, Kofler, Alderson, & Raiker, 2008). Ten (50%) of the ADHD children were on a regimen of psychostimulants for treatment of their ADHD symptoms (24 hour washout period prior to each clinic testing sessions). One of the ADHD children was diagnosed with comorbid Oppositional-Defiant Disorder (ODD). None of the children were comorbid for additional DSM-V childhood disorders.

Fourteen children 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 SDs of the mean on all CBCL and TRF scales; and (4) parent and teacher ratings within the non-clinical range on all CSI subscales¹.

Measures

Phonological Working Memory Tasks

The phonological (PH) working memory tasks used in the current study are identical to those described by Rapport, Alderson et al. (2008). Each child was administered four phonological conditions (i.e., PH 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 indicate large magnitude between-group differences on these tasks (Rapport, Alderson et al. 2008), and performance on these tasks predicts ADHD-related impairments in objectively measured activity level (Rapport et al., 2009), impulsivity (Raiker, Rapport, Kofler, & Sarver, 2012) and attentive behavior (Kofler, Rapport, Bolden, Sarver, & Raiker, 2010). The working memory measure tasks also have high internal consistency ($\alpha = 0.82$ to 0.97) and the expected level of external validity ($r = .50$ to $.66$) with WISC-III and -IV Digit Span short-term memory raw scores (Raiker et al., 2012).

¹ Two TD children had scores at/above 1.5 SDs on one or more CSI and/or CBCL parent but not teacher scales; these children were included given K-SADS parent and child interviews and developmental histories were negative for all clinical disorders including ADHD. Additionally, one ADHD child had elevated but not clinical range scores on the teacher ADHD questionnaires that were likely attributable to a strict psychostimulant regimen. The overall pattern of results was unchanged with these children excluded.

The phonological working memory tasks are similar to the Letter-Number Sequencing subtest on the WISC-IV (Wechsler, 2003), and assesses 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 correctly recalled as 2 4 6 H). Children completed five practice trials prior to each administration ($\geq 80\%$ correct required). Two trained research assistants, shielded from the participant's view, listened to the children's vocalizations and recorded oral responses independently. Interrater reliability was calculated for all task conditions for all children, and ranged from .97 to 1.0.

Information Processing Tasks

The information processing tasks described below were administered in a counterbalanced order across the four Saturday testing sessions such that each child received each task on two occasions, one week apart, to improve precision via removal of random and session-specific (test-retest) error². The tasks were designed experimentally such that each task required a specific combination of the information processing subcomponents shown in Figure 2,

² Scores for the two administrations of each task were combined using principal components factor analysis. A 1-factor solution was preferred for all constructs based on first factor eigenvalue > 1.0 and second factor eigenvalue < 1.0 . Factor loadings and eigenvalues are reported for each measure.

allowing a regression-based, latent variable approach to statistically isolate reliable variance associated with each information processing stage.

Picture naming task

The Picture Naming Task required children to visually register and encode pictures (visual registration and encoding), convert these visual stimuli to phonological code (orthographic to phonological conversion), verbally indicate the object's name, and simultaneously press a response key (response preparation, skeletomotor speed). Verbal responses were required to ensure task engagement and orthographic-to-phonological conversion; five practice trials were administered with coaching and repeated until children successfully responded to all 5 trials (i.e., correctly named each object while simultaneously pressing the response key). We selected 30 monochrome stimuli from an open-source clipart repository based on the criteria that they were clearly drawn and easily recognizable archetypes, and had monosyllabic names (e.g., car, dog). An additional 30 monochrome stimuli were included and consisted of unique Chinese symbols, to which children were trained to respond "No". These unfamiliar stimuli were added as catch trials to decrease the likelihood of anticipatory responding, as part of a larger study examining serial/parallel long-term memory search termination processes, and are not included in the calculation of the primary indices described below.

The task displayed 60 visual stimuli (30 familiar, 30 unfamiliar) in random order at an average rate of one stimulus/second (jittered randomly between 800, 1000, and 1200 ms to decrease anticipatory responding). Anticipatory responses (trial RT < 150 ms) were excluded as recommended (Hervey et al., 2006; Karalunas, Huang-Pollock, & Nigg, 2012). Mean reaction

time for correct responses across the 30 familiar object trials served as the primary outcome variable. The task was administered twice, one week apart, with a different, randomized presentation order each time; the same 60 stimuli were used across administrations of the Picture Naming and Picture RT task (described below). A latent Picture Naming factor score was computed via principal components factor analysis (both factor loadings = .92; eigenvalue = 1.69) and reflects reliable variance associated with all of the information processing subcomponents shown in Figure 2.

Picture reaction time (RT) task

A novel simple reaction time (SRT) task was created to be identical to the Picture Naming Task described above in every aspect except the orthographic-to-phonological conversion demands. As shown in Figure 2, the Picture RT task required children to visually register/encode and provide a skeletomotor response to each visually presented stimuli. The same 60 stimuli described in the Picture Naming tasks were used to equate these counterbalanced tasks as closely as possible. Children were instructed to press a response key as quickly as possible each time any picture appeared, regardless of its content. Five practice trials were administered with coaching until children successfully responded to all 5 trials; children were explicitly instructed not to name the objects when necessary (e.g., children whose counterbalancing resulted in them completing the Picture Naming tasks in previous sessions). Examination of raw task performance suggested that the experimental manipulation (addition of orthographic-to-phonological conversion demands for Picture Naming vs. Picture RT) was successful based on significantly longer mean RTs during the Picture Naming (MRT = 963.88 ms) relative to Picture RT tasks (MRT = 438.87 ms; $p < .0001$).

Jittered stimulus display rate, number of stimuli (60), and all task demands except the instruction to name each object were identical to the Picture Naming task described above. Anticipatory responses (trial RT < 150 ms) were excluded (Hervey et al., 2006; Karalunas et al., 2012). Mean reaction time for correct responses across the 30 familiar object trials served as the primary outcome variable to equate performance across the Picture Naming and Picture RT tasks. Like Picture Naming, the Picture RT task was administered twice, one week apart, with a different, randomized presentation order each time. A latent Picture RT factor score was computed via principal components factor analysis (both factor loadings = .84; eigenvalue = 1.41) and reflects reliable variance associated with the visual registration/encoding, and response preparation/skeletomotor speed subcomponents of the information processing model shown in Figure 2.

Motor speed task

A novel motor speed task was used to assess skeletomotor speed. Children were instructed to repeatedly press a response key as quickly and as many times as possible for 10 seconds using their dominant hand. The task was designed to index children's basic skeletomotor speed independent of the additional processes associated with encoding and responding to a stimulus; the short duration was selected to minimize fine motor muscle fatigue following pilot testing. A 10-second practice trial was administered prior to each administration to ensure task comprehension. The number of presses per second served as the dependent variable. The motor speed task was administered twice, one week apart. A latent Motor Speed factor score was computed via principal components factor analysis (both factor loadings = .80; eigenvalue =

1.28) and reflects reliable variance associated with the response preparation and skeletomotor speed subcomponents of information processing (Figure 2).

Measured intelligence

All children were administered the Wechsler Intelligence Scale for Children fourth edition to obtain an overall estimate of intellectual functioning based on each child's estimated Full Scale IQ (FSIQ; Wechsler, 2003).

Dependent Variables

Phonological working memory

A latent factor reflecting phonological working memory performance (i.e., phonological storage/rehearsal processes operating in tandem with central executive processes) was created using the recommended methods (cf. Kofler et al., 2014) to extract reliable (shared) variance across all four phonological working memory set size conditions (all factor loadings $\geq .78$; eigenvalue = 2.71).

Visual registration and encoding

As shown in Figure 2, a primary difference between the Picture RT and Motor Speed tasks is the requirement to respond to visually presented stimuli in the former but not the latter. Therefore, visual registration and encoding was estimated by residualizing the Picture RT factor score for the Motor Speed factor score ($R^2 = .001$). As indicated by the very small R^2 , performance on the Picture RT task was minimally influenced by individual differences in skeletomotor speed. Thus, residualizing the Picture RT task in this manner provided minimal

incremental improvement in our estimates; all results below were unchanged when using the unresidualized vs. residualized factor scores.

Orthographic-to-phonological conversion

As shown in Figure 2, the primary difference between the Picture Naming and Picture RT tasks is the requirement to convert the visually-presented (orthographic), familiar objects to phonological code in the former but not the latter. All other task requirements are identical (e.g., same stimuli, same visual registration, encoding, response preparation, and skeletomotor response requirements). Therefore, orthographic to phonological conversion was estimated by residualizing the Picture Naming factor score for the Picture RT factor score ($R^2 = .07$). Given that random and session-specific error was previously removed from these factor scores as detailed above, residual variance in Picture RT reflects reliable variance associated with orthographic-to-phonological conversion after removing performance associated with visual registration and encoding, and response preparation and skeletomotor speed.

Response preparation and skeletomotor speed

As shown in Figure 2, the latent Motor Speed factor score described above served as the primary index of response preparation and skeletomotor speed. To facilitate interpretation, this factor was reverse scored (i.e., multiplied by -1) so that higher scores reflect worse (slower) performance for all information processing metrics.

Procedures

All children participated in four consecutive Saturday assessment sessions. All tasks were administered as part of a larger battery that required the child's presence for approximately 3 hours per session. All tasks were counterbalanced across testing sessions to minimize order

effects. Children completed all tasks while seated alone 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 (Gomez & Sanson, 1994; Power, 1992). All children 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. Children were seated approximately 0.66 m from the computer monitor for all tasks.

Due to experimenter error, three ADHD children received the same stimuli order for both administrations of Picture Naming ($n = 2$) or Picture RT ($n = 1$), and two ADHD children completed the Picture Naming ($n = 1$) or Picture RT ($n = 1$) task only once. No significant differences were detected between these children and the children receiving parallel forms of stimuli presentation order as expected given the unlikelihood of remembering the serial order of 60 stimuli a week later. Therefore, these children were retained and group mean substitution was used for the children with missing data to allow computation of factor scores.

Analysis Overview

A two-tiered data analytic approach was employed to examine the study's primary hypotheses. Intercorrelations between diagnostic status and the phonological working memory and information processing factor scores (visual registration/encoding, orthographic to phonological conversion, and response preparation/skeletomotor speed) were computed in Tier I to determine whether mediation analyses were justified. Any variables related significantly to ADHD status (0 = ADHD, 1 = TD) were retained in Tier II. Tier II used bias-corrected,

bootstrapped mediation analyses (described below) to test the extent to which any identified impairments in lower-level information processing subcomponents contributed to higher-order phonological working memory performance deficits associated with ADHD.

Mediation Analysis

All analyses were completed using a bias-corrected bootstrapping procedure to minimize Type II error following the steps recommended by Shrout and Bolger (2002). Bootstrapping is appropriate for total sample sizes as low as 20 (Efron & Tibshirani, 1993), and was used to estimate and determine the statistical significance of all total, direct, and indirect effects. All continuous variables were standardized as 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 = 34) by a process of resampling with replacement (Shrout & Bolger, 2002).

Bias-corrected bootstrapping was used to estimate and determine the statistical significance of all total, direct, and indirect effects. Adopting mediation analysis terminology, the total effect represents the relation between diagnostic status (ADHD, TD) and phonological working memory prior to examining whether information processing subcomponents serve as a significant mediator of this relation (Figure 3, path c). In contrast, the direct effects represent the regression coefficients across models for diagnostic status (ADHD, TD) predicting each information processing subcomponent (Figure 3, path a), as well as each information processing

subcomponent predicting children's phonological working memory (Figure 3, path b) after controlling for diagnostic status. The magnitude of the pathway in which diagnostic status predicts phonological working memory scores after accounting for the potential mediating influence of lower-level information processing subcomponents also is considered a direct effect and is reported separately (Figure 3, path c'). The residual difference in effect magnitude before (c pathway) and after (c' pathway) accounting for the mediating variable reflects the indirect effect for each of the mediating pathways (Figure 3, path ab).

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, 90% confidence intervals for indirect effects, and effect ratios (ER) are shown in Figures 3b and 3c, and Table 3. Ninety percent confidence intervals were selected over 95% confidence intervals because the former are more conservative for evaluating mediating effects (Shrout & Bolger, 2002)³.

³ Briefly, the wider 95% confidence interval increases the likelihood that the confidence interval for c' will include 0.0, indicating that diagnostic status and the dependent variable are no longer related significantly after accounting for the mediator (i.e., full mediation in Baron & Kenny, 1986, terminology). In contrast, the narrower 90% confidence interval is less likely to include 0.0, and therefore is likely to result in a more conservative conclusion regarding the magnitude of the relation between diagnostic status and the dependent variable after accounting for the mediator (i.e., partial mediation). For discussion and specific examples of this phenomenon, see Shrout and Bolger (2002).

CHAPTER 3: RESULTS

Preliminary Analysis

All independent and dependent variables were screened for univariate outliers as reflected by scores exceeding 3.5 standard deviations from the mean in either direction and no outliers were identified (Tabachnick & Fidell, 2007). Sample race and ethnicity included 23 Caucasian (67.6%), 7 Hispanic (20.6%), and 4 biracial (11.8%) children. 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). Similarly, children with ADHD did not differ in age ($p = .09$), FSIQ ($p = .10$), or SES ($p = .65$) relative to typically developing children. As a result, simple model results with no covariates are reported for all analyses to allow for the B coefficients to be interpreted as Cohen's d effect sizes (Hayes, 2009).

Tier I: Intercorrelations

Intercorrelations between all factor scores were computed via bootstrapping (90% confidence intervals) as a first step to determine whether mediation analyses were justified (Table 2). A diagnosis of ADHD (0 = ADHD, 1 = TD) was related significantly to impaired phonological working memory performance ($r = -.45$; 90% CI = $-.28$ to $-.62$; $p = .007$), slower visual registration and encoding ($r = .40$; 90% CI = $.18$ to $.63$; $p = .02$), and slower conversion of orthographic stimuli to phonological code ($r = .34$; 90% CI = $.06$ to $.58$; $p = .049$), but was not related significantly to response preparation/skeletomotor speed ($r = -.27$; 90% CI = $-.01$ to $.55$; $p = .12$). Skeletomotor speed was not

related significantly to any other included variables (all other $p > .37$) and was therefore not examined as a potential mediator in Tier II; all other variables were retained for Tier II.

Tier II: Mediation Analyses

Standardized B weights (interpreted as Cohen's d effect sizes when predicting from the dichotomous grouping variable; Hayes, 2009), standard errors, and 90% confidence intervals for all bias-corrected, bootstrapped analyses are displayed in Table 3.

Total effect

Examination of the total effect (Figure 3 path c; Table 3) revealed that diagnostic status (ADHD, TD) was related significantly to phonological working memory (Cohen's $d = -0.91$), such that children with ADHD demonstrated large magnitude deficits in phonological working memory prior to accounting for the potential mediating role of lower-level information processing subcomponents.

Skeletomotor speed mediating phonological working memory

Skeletomotor speed was not tested as a potential mediator given its nonsignificant relations with diagnostic status and all other factor scores.

Visual registration/encoding mediating phonological working memory

As shown in Figure 3b and Table 3 (first column), an ADHD diagnosis was associated significantly with slower registration and encoding of visual stimuli (Cohen's $d = 0.78$; Figure 3b, path a). In addition, slower visual registration/encoding was associated with worse phonological working memory performance ($B = -.37$; Figure 3b, path b) after controlling for diagnostic status. Examination of the mediation pathway (Figure 3b, path ab) revealed that diagnostic status exerted a significant, small magnitude indirect effect on phonological working memory (Cohen's $d = -0.29$, 90% confidence

interval = -0.81 to -0.07) through its impact on lower-level visual registration and encoding processes. In doing so, it was associated with a moderate reduction in the magnitude of ADHD-related phonological working memory deficits (d changed from -0.91 to -0.62; ER = .32). The relation between diagnostic status and phonological working memory remained significant ($d = -0.62$, 90% CI = -1.17 to -0.07). Examination of the effect ratio indicated that approximately one-third (32%) of the relation between ADHD diagnostic status and phonological working memory deficits was attributable to the indirect effect of lower-level visual registration and encoding processes; medium rather than large magnitude between-group differences in phonological working memory remained after accounting for this relation.

Orthographic-to-phonological conversion mediating phonological working memory

As shown in Figure 3c and Table 3 (second column), an ADHD diagnosis was associated significantly with slower conversion of orthographic stimuli to phonological code (Cohen's $d = 0.67$; Figure 3c, path a). In contrast, orthographic to phonological conversion processes were not associated significantly with phonological working memory performance ($B = .001$; Figure 3c, path b). Examination of the mediation pathway (Figure 3c, path ab) revealed a nonsignificant indirect effect (Cohen's $d = 0.0008$, 90% confidence interval = -.23 to .18; Figure 3c, path ab) as indicated by the confidence interval that included 0.0. Collectively, results of this model indicate that children with ADHD take moderately longer than their peers to convert orthographic information to phonological code, but that this medium magnitude impairment is not significantly related to their difficulties on phonological working memory tasks.

Table 1. Sample and Demographic Variables

Variable	ADHD		Typically Developing		<i>F</i>
	\bar{X}	<i>SD</i>	\bar{X}	<i>SD</i>	
Age	9.47	1.09	10.18	1.30	2.99
FSIQ	103.55	8.86	109.64	12.15	2.87
SES	52.73	8.07	51.11	12.84	.204
CBCL					
AD/HD Problems	70.35	8.37	53.21	7.20	38.60****
TRF					
AD/HD Problems	68.00	7.26	52.93	5.54	42.73****
CSI-Parent					
ADHD, Combined	77.60	9.74	46.57	11.69	70.95****
CSI-Teacher					
ADHD, Combined	69.10	8.15	45.43	5.66	88.25****
Cohen's <i>d</i>					
Skeletomotor Speed Factor Score	-0.23	1.09	0.32	0.79	0.55
Visual Encoding Factor Score	0.32	0.89	-0.46	0.96	0.78*
Orthographic Conversion Factor Score	0.28	0.87	-0.39	1.03	0.67*
Phonological Working Memory Factor Score	-0.37	1.08	0.53	0.55	-0.91**

Note: ADHD = attention-deficit/hyperactivity disorder; CBCL = Child Behavior Checklist; CSI = Child Symptom Inventory severity *T*-scores; FSIQ = Full Scale Intelligence Quotient; SES = socioeconomic status; TRF = Teacher Report Form.

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

Table 2. Intercorrelations among variables

	1	2	3	4	5
1. Diagnostic status (ADHD, TD)					
2. PH Working Memory	-.45**				
3. Response Preparation/Skeletomotor Speed	-.27	-.15			
4. Visual Registration and Encoding	.40*	-.49**	<i>0.0</i>		
5. Orthographic to Phonological Conversion	.34*	-.15	.06	<i>-.001</i>	

Note: Correlations with group are biserial correlations. *Italicized* correlations reflect relations not expected to be significant due to the factor score residual approach that isolated reliable, unique variance associated with each information processing subcomponent.

ADHD = attention-deficit/hyperactivity disorder; PH = phonological; TD = typically developing

* $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$. All other $p > .12$

Table 3. Mediation analyses: Impact of diagnostic status (ADHD, TD) and information processing subcomponents on phonological working memory

Path		Processing Speed			
		Visual Registration/ Encoding		Orthographic to Phonological Conversion	
<u>Total Effect</u>		<i>d</i>	(SE)	<i>d</i>	(SE)
c	Diagnosis → PH Working Memory	-91	(.32)	-91	(.32)
	90% CI	-1.44 to -.37		-1.44 to -.37	
<u>Direct Effects</u>					
a	Diagnosis → Processing Speed	.78	(.32)	.67	(.33)
	90% CI	.24 to 1.33		.12 to 1.23	
b	Processing Speed → PH Working Memory	-.37	(.16)	.001	(.17)
	90% CI	-.65 to -.09		-.29 to .29	
c'	Diagnosis → PH Working Memory	-.62	(.32)	-.91	(.34)
	90% CI	-1.17 to -.07		-1.49 to -.33	
<u>Indirect Effects (through mediator)</u>					
ab	Diagnosis → PH Working Memory				
	Bootstrap Estimate	-.29*	(.20)	.0008	(.12)
	90% CI of Bootstrap	-.81 to -.07		-.23 to .18	
Effect Ratio		.32		--	

Note: The PROCESS macro for SPSS (Hayes, 2013) was used to perform bias-corrected bootstrapping for all analyses. Paths labels reflect standard nomenclature (cf. Fritz & MacKinnon, 2007) and are depicted in Figure 3; c and c' reflect the total and direct effect of Diagnosis on PH working memory before and after accounting for each information processing subcomponent; PH = phonological *Effect size (or B-weight) is significant based on 90% confidence intervals that do not include 0.0 (Shrout & Bolger, 2002); ¹Values in the *d* column for path b do not reflect effect size values due to the use of two continuous variables in the calculation of the direct effect.

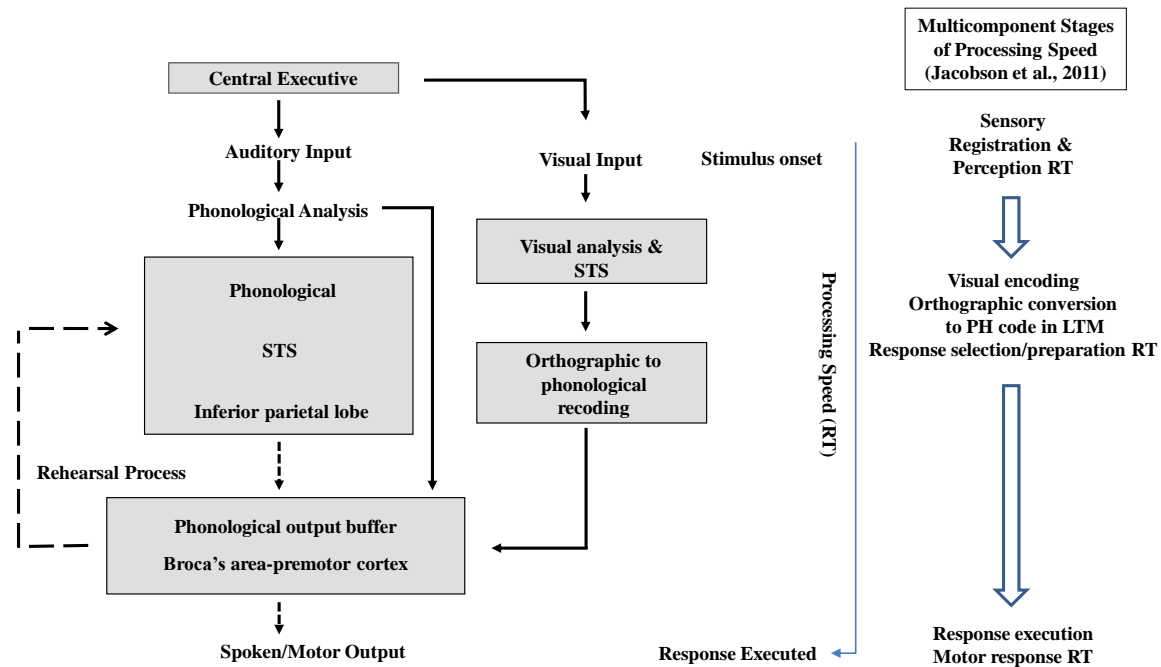


Figure 1. Adapted and expanded version of Baddeley's (2007) phonological working memory subsystem and corresponding components of processing speed from stimulus onset to response output based on Jacobson et al. (2011). PH = Phonological. LTM = Long-term Memory. RT = Reaction time. STS = Short-term store. Reprinted and expanded with permission from the author.

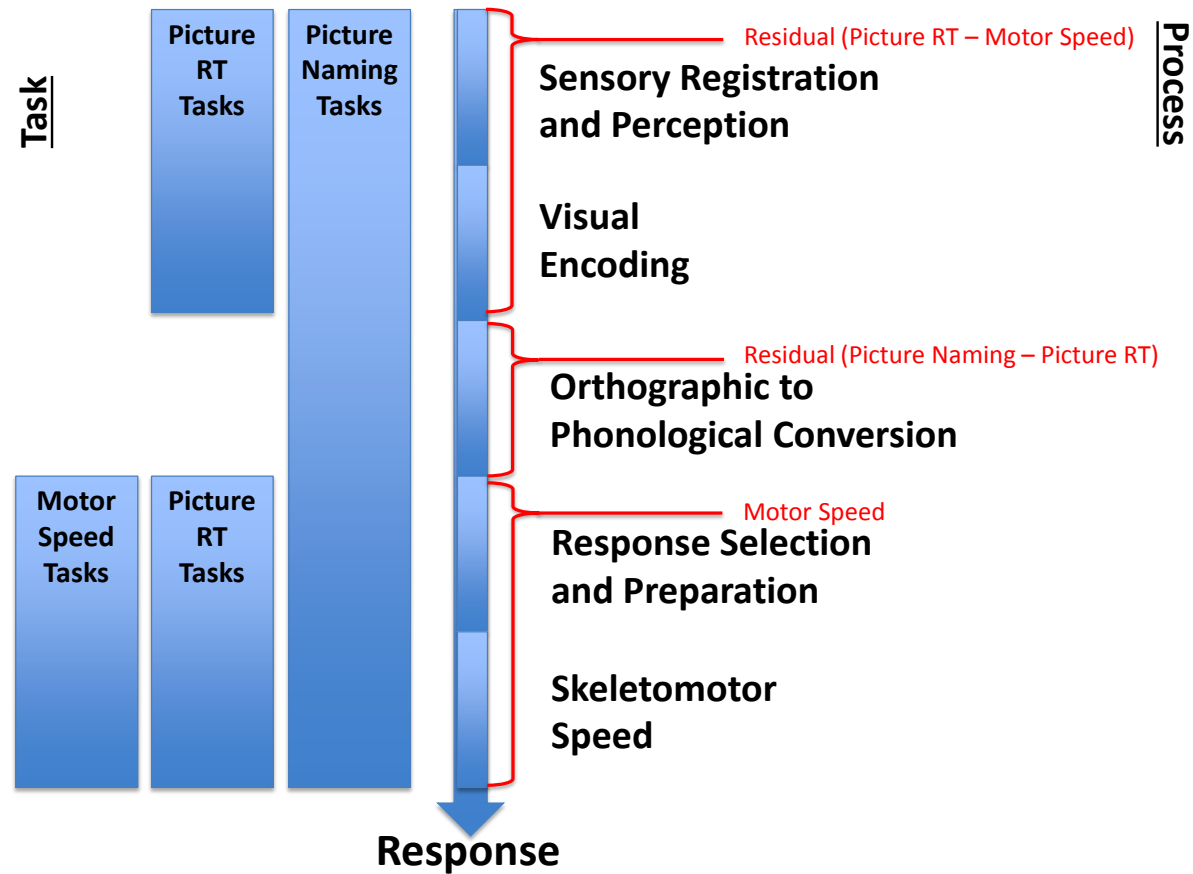


Figure 2. Schematic illustrating the information processing subcomponents examined in the current study (middle column), the experimental tasks used to derive indices of each information processing subcomponent (left), and the statistical method for deriving reliable variance associated with each subcomponent (right). RT = reaction time.

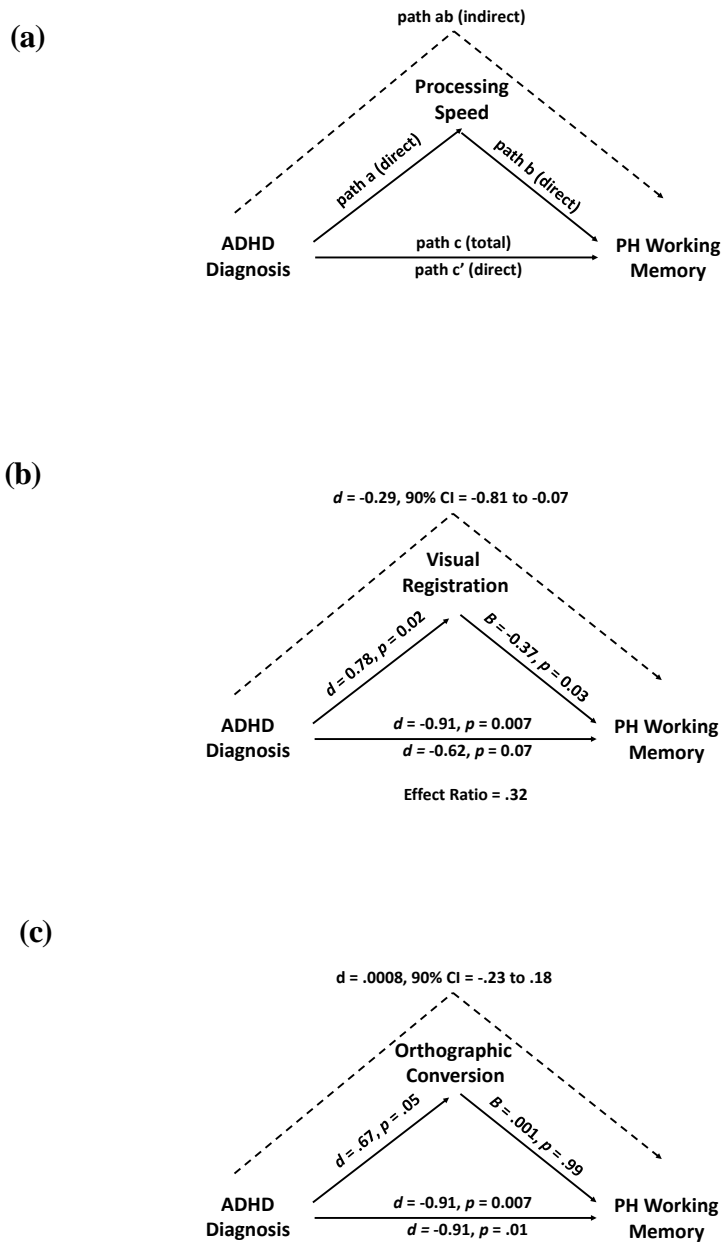


Figure 3. Schematic depicting (a) the effect sizes and B coefficients of the total, direct, and indirect pathways for the mediating effect of (b) visual registration and encoding and (c) orthographic-to-phonological conversion on phonological working memory.

CHAPTER 4: DISCUSSION

The well-documented working memory deficits associated with ADHD (cf. Kasper et al., 2012), combined with the inefficacy of current medications (Rubia et al., 2013) and cognitive training programs (Rapport et al., 2013) for targeting brain regions associated with working memory, provide a compelling impetus for neurocognitive research examining the interrelations among component pieces of these systems. In particular, the phonological system's intricate involvement in multiple aspects of academic functioning and aptitudes (Alloway et al., 2004; Montgomery, 1995; Swanson & Howell, 2001; Cain et al., 2004) underscores the importance of dissociating its underlying, lower-level cognitive subprocesses to better understand the nature of phonological working memory deficits in children with ADHD. The current study reflects one piece of this puzzle, and is the first to disassociate and examine the contribution of three critical subcomponents of lower-level information processing (Figure 2) to higher-order phonological working memory performance for children with and without ADHD.

Consistent with meta-analyses (Willcutt et al., 2005; Kasper et al., 2012), summative literature reviews (Sergeant et al., 2002), and empirical evaluations (Holmes et al., 2010; Rapport, Alderson et al., 2008), the current study revealed large magnitude phonological working memory deficits in children with ADHD (Cohen's $d = -0.91$). In contrast, no impairments in basic response preparation and skeletomotor speed were detectable. Although this latter finding was somewhat unexpected given the replicated finding of slower and more variable reaction times in children with ADHD (Kofler et al., 2013), the vast majority of previous studies have not disassociated basic motor speed from additional information processing subcomponents such as early registration and encoding (required for even

simple reaction time tasks), orthographic to phonological conversion and/or choice decision processes (for tasks requiring evaluation of stimuli and/or multiple response options), and response inhibition demands (e.g., for more complex go/no-go and Flanker tasks). In contrast, our findings are largely consistent with the only other study to date that examined the independent contribution of (graphomotor) motor speed in ADHD (Jacobson et al., 2011). Concluding that basic skeletomotor speed is likely intact in ADHD is also consistent with longitudinal fMRI studies suggesting that the primary motor cortex matures faster in children with ADHD relative to the general population (Shaw et al., 2007).

In contrast, children with ADHD demonstrated significant impairments in the visual registration and encoding (Cohen's $d = 0.78$) and orthographic to phonological conversion (Cohen's $d = 0.67$) stages of early information processing. These findings converge with past reports of overall slower completion rates for children with ADHD on tasks that require a combination of these and other lower-level processes (Banaschewski et al., 2006; Carte et al., 1996; Lawrence et al., 2004; Semrud-Clikeman et al., 2000; Rucklidge & Tannock, 2002; Shanahan et al., 2006; Tannock et al., 2000), and provide initial evidence implicating visual encoding and orthographic conversion, but not basic skeletomotor speed, in these overall performance patterns. The findings are also generally consistent with an emerging literature reporting that children with ADHD mentally accumulate information less quickly and efficiently than their peers based on sophisticated diffusion modeling that statistically disassociates mental processes involved in 2-choice reaction time tasks (i.e., slower drift rate and non-decision time components; Huang-Pollock, Karalunas, Tam, & Moore, 2012; Karalunas, Geurts, Konrad, Bender, & Nigg, 2014; Karalunas & Huang-Pollock, 2013; Karalunas et al., 2012). Notably, our use of simple,

single-choice RT tasks (relative to the 2-choice RT tasks required for diffusion modeling), suggests that information processing deficiencies may occur at an even lower level than previously hypothesized.

Examining the extent to which these lower-level processes were associated with higher-order phonological working memory deficits, however, was of greater interest. Interestingly, meditation analyses revealed that children's visual registration and encoding speed, but not their ability to rapidly convert orthographic information to phonological code, significantly mediated the relation between ADHD diagnostic status and phonological working memory performance. The most parsimonious explanation for these findings appears to be that ADHD children's slowed registration and encoding of visual information restricts the rate at which information becomes available for rehearsal and processing within the phonological working memory system. In other words, slowed movement of visual information through the early stages of information processing appears to create a 'bottleneck' that limits the rate at which the phonological storage/rehearsal system gains access to this information. Rapid access to information is critical for maximizing higher-order processing capacity given the rapid degradation of information from the phonological short-term store unless that information is actively rehearsed every 2 to 3 seconds (Baddeley, 2007). Inefficient entry into the short-term store, in turn, places clear limits on higher-order information processing within phonological working memory (e.g., mental manipulation) and is associated with impaired learning across a wide range of academic areas including reading (Durand et al., 2005), math (Alloway & Alloway, 2010), and science (Gathercole et al., 2004). The current findings of partial mediation are consistent with this view, and suggest that both lower-level information processing and higher-order working memory processing contribute to phonological working memory deficits in ADHD.

It seemed likely that ADHD children's phonological working memory performance would be further impaired by their inefficient conversion of orthographic information into phonological code; however, the nonsignificant mediation effect for this construct, despite medium magnitude between-group differences ($d = 0.67$), was inconsistent with this view and suggests that ADHD children's slowed orthographic to phonological conversion abilities exert minimal impact on their phonological working memory deficits. One potential explanation for this discrepancy may be that the magnitude of their phonological conversion impairment was insufficient to result in problems given the stimulus presentation rate on the phonological working memory task. Examination of the raw data suggests that children with ADHD take, on average, 172 ms longer than TD children to convert a visually-presented stimulus to phonological code⁴. Thus, their slowed orthographic-to-phonological conversion abilities may not have interfered with performance on working memory tasks that allowed 1000 ms per stimuli (800 ms presentation, 200 ms interstimulus interval) – i.e., the working memory tasks' parameters allowed sufficient time to compensate for their overall slowed orthographic-to-phonological conversion abilities. Future research using shorter presentation durations and/or more complex stimuli to be encoded and converted (e.g., sentences vs. single digit numbers and letters) are needed to test the extent to which slowed orthographic to phonological conversion impairs higher-order processing in academic and other settings that place relatively heavy demands on the phonological system.

Taken together, the study's primary findings suggest that basic visual registration and encoding difficulties account for approximately one-third of ADHD children's phonological working memory

⁴ Computed as the raw difference in milliseconds between each group's mean response time on the Picture Naming and Picture RT tasks, based on the methodological rationale presented earlier (ADHD = 611.01 ms, TD = 439.01 ms).

deficits (Δd from -0.91 to -0.62), highlighting the role of both lower-level (visual registration/encoding) and higher-order (working memory storage, rehearsal, and processing) processes in these children's well-documented working memory deficits. Given this finding, one might hypothesize that children with ADHD would benefit from auditory presentation of to-be-processed information. Recent experimental evidence using auditory and visual variants of the phonological working memory task, however, suggests that auditory presentation may result in larger magnitude impairments relative to visual presentation (Alderson et al., 2014). This finding highlights the equifinality characteristic of the ADHD phenotype (Nigg, 2005), as well as the diverse cortical regions that are underdeveloped in many children with ADHD (Shaw et al., 2007). Furthermore, it suggests that next-generation working memory training programs may exert maximum benefits by individually tailoring intervention components to each child's neurocognitive profile and targeting more than short-term storage capacity (Chacko et al., 2013; Gibson et al., 2010; Rapport et al., 2013).

The distinctiveness of the lower-level information processing stages and their unique associations with phonological working memory performance is consistent with their unique neuroanatomical circuitry. For example, visual registration is localized primarily to the superior parietal and supplementary motor area regions (Ganis, Thompson, Kosslyn, 2004; Houdé, Rossi, Lubin, & Joliot, 2010; Tan, Laird, Li, & Fox, 2005), both of which are implicated in verbal working memory (Jonides et al., 1998; Schumacher et al., 1996). In contrast, tasks involving orthographic to phonological conversion correspond with inferior parietal and temporal regions (Houdé et al., 2010; Tan et al., 2005). Further, both processes recruit left inferior frontal areas (Booth et al., 2004), whereas concurrent use of these processes in tandem is associated with additional activation in the *visual word form* area of the fusiform cortex (Price & Devlin, 2003; Tan et al., 2005). Anatomical studies examining these regions

in children with ADHD and relevant clinical controls are needed to determine whether these deficits are unique to ADHD or transdiagnostic pathways responsible for the impaired working memory functioning detected in diverse disorders spanning ADHD (Kasper et al., 2012), reading disability (Martinussen & Tannock, 2006), and depression (Snyder, 2013) among others.

The impact of lower-level information processing – particularly visual registration and encoding – on ADHD children’s phonological working memory deficits has important implications for interventions aimed at improving behavioral symptoms and functional outcomes (e.g., academic performance and aptitude) associated with the disorder. The failure of current cognitive interventions to attenuate working memory, behavioral, or functional impairments (cf. Rapport et al., 2013) may be due to their narrow focus on improving the less impaired aspects of working memory functioning (i.e., short-term storage; Chacko et al., 2013) as well as a lack of focus on remediating more basic cognitive processes (e.g., visual registration/encoding) necessary for optimal working memory functioning. Future interventions may benefit from the inclusion of adaptive training of lower-level information processing by varying the speed with which visual information must be processed and explicitly training orthographic to phonological conversion speed. Adaptive training methodology is well suited for this purpose and can make continual, ongoing adjustments in presentation rate and how quickly answers must be inputted based on children’s intraindividual and intra-session performance. Demonstration of training effects, near-transfer effects, and far-transfer measures will be key to assessing the extent to which these hypothesized mechanisms are improved and, more importantly, result in improvements in critical functional domains such as academic competencies.

Despite methodological (e.g., multiple administrations of each task and dissociation of multiple components of information processing) and statistical (e.g., bootstrapped mediation) refinements,

limitations are inherent to all research investigations. Specifically, future studies are likely to benefit from larger and more diverse samples that include females, younger children, and adolescents with ADHD, and children comorbid for learning disabilities and processing disorders. The sample size of the current study was moderate due to the extensive hours required to complete a single child's evaluation,⁵ but sufficiently robust given the bias-corrected, bootstrapped mediation approach used as recommended (Efron & Tibshirani, 1993; Shrout & Bolger, 2002).

Collectively, the current study adds to an emerging literature implicating both lower-level and higher-order neurocognitive deficits in ADHD. Specifically, the inefficient registration of visual information slows the rate at which information becomes accessible within phonological working memory, resulting in a bottleneck that is likely compounded by the rapid degradation of information from the short-term store unless that information is actively refreshed by means of covert or overt rehearsal (Baddeley, 2007). Taken together with the results of previous studies, it appears that the phonological working memory system in childhood ADHD may be characterized by an access bottleneck and rapid degradation of information in the short-term store, decreased overall capacity (cf. Martinussen et al., 2005), an impaired rehearsal mechanism (Bolden, Rapport, Raiker, Sarver, & Kofler, 2012), and an underdeveloped central executive responsible for system oversight and higher-order processing of information held in the short-term storage system (Kasper et al., 2012; Rapport et al., 2013). The extent to which lower-level information processing deficits exert their effect on the phonological storage/rehearsal system relative to the domain-general central executive remains unknown, but warrants investigation

⁵ 120 or more person hours are required to complete a single child's evaluation due to their participation in multiple studies and the provision of a comprehensive clinical report and full parental debriefing.

given the critical involvement of the phonological working memory system to reading and mathematics aptitude and a wide range of learning outcomes (Sarver et al., 2012).

APPENDIX: IRB APPROVAL LETTER



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 and Co-PI: Valerie K. Sims**

Date: **December 16, 2013**

Dear Researcher:

On 12/16/2013, the IRB approved the following human participant research until 12/15/2014 inclusive:

Type of Review: IRB Continuing Review Application Form
Project Title: Attention Deficit/Hyperactivity Disorder (ADHD): The Role of Working Memory as a Core Deficit
Investigator: Mark D Rapport
IRB Number: SBE-07-04348
Funding Agency:
Grant Title:
Research ID: SBE-07-04348

The scientific merit of the research was considered during the IRB review. The Continuing Review Application must be submitted 30 days 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 12/15/2014, 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).

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:

Signature applied by Joanne Muratori on 12/16/2013 09:48:44 AM EST

IRB Coordinator

LIST OF REFERENCES

- Achenbach, T.M., & Rescorla, L.A. (2001). Manual for the ASEBA school-age forms & profiles. Burlington: University of Vermont Research Center for Children, Youth, & Families.
- Alderson, R.M., Kasper, L.J., Patros, C.H., Hudec, K.L., Tarle, S.J., & Lea, S.E. (2014). Working memory deficits in boys with attention deficit/hyperactivity disorder (ADHD): An examination of orthographic coding and episodic buffer processes. *Child Neuropsychology*, (ahead-of-print), 1-22.
- Alloway, T.P., & Alloway, R.G. (2010). Investigating the predictive roles of working memory and IQ in academic attainment. *Journal of Experimental Child Psychology*, 106, 20-29.
- Alloway, T.P., Gathercole, S.E., Willis, C., & Adams, A. (2004). A structural analysis of working memory and related cognitive skills in young children. *Journal of Experimental Child Psychology*, 87, 85-106.
- American Psychiatric Association. (2013). *Diagnostic and Statistical Manual of Mental Disorders: DSM-5™ (5th ed.)*. Arlington, VA: American Psychiatric Publishing, Inc.
- Baddeley, A. (2007). *Working memory, thought, and action*. New York: Oxford University Press.
- Baddeley, A. (2012). Working memory: Theories, models, and controversies. *Annual Review of Psychology*, 63, 1-29.
- Ballesteros, S., Reales, J.M., García, B. (2007). The effects of selective attention on perceptual priming and explicit recognition in children with attention deficit and normal children. *European Journal of Cognitive Psychology*, 19, 607-627.

- Banaschewski, T., Ruppert, S., Tannock, R., Albrecht, B., Becker, A., Uebel, H. . . Rothenberger, A. (2006). Colour perception in ADHD. *Journal of Child Psychology and Psychiatry*, *47*, 568-572.
- Barkley, R.A. (1997). Behavioral inhibition, sustained attention, and executive functions: Constructing a unifying theory of ADHD. *Psychological Bulletin*, *121*, 65-94.
- Baron, R.M., & Kenny, D.A. (1986). The moderator-mediator variable distinction in social psychological research: Conceptual, strategic, and statistical considerations. *Journal of Personality and Social Psychology*, *51*, 1173–1182.
- Bolden, J., Rapport, M.D., Raiker, J.S., Sarver, D.E., & Kofler, M.J. (2012). Understanding phonological memory deficits in boys with attention-deficit/hyperactivity disorder (ADHD): Dissociation of short-term storage and articulatory rehearsal processes. *Journal of Abnormal Child Psychology*, *40*, 999-1011.
- Booth, J.R., Burman, D.D., Meyer, J.R., Gitelman, D.R., Parrish, T.B., & Mesulam, M. (2004). Development of brain mechanisms for processing orthographic and phonologic representations. *Journal of Cognitive Neuroscience*, *16*, 1234-1249.
- Cain, K., Oakhill, J., & Bryant, P. (2004). Children’s reading comprehension ability: Concurrent prediction by working memory, verbal ability, and component skills. *Journal of Educational Psychology*, *96*, 31-42.
- Carte, E.T., Nigg, J.T., & Hinshaw, S.P. (1996). Neuropsychological functioning, motor speed, and language processing in boys with and without ADHD. *Journal of Abnormal Child Psychology*, *24*, 481-498.

- Chacko, A., Feirsen, N., Bedard, A.C., Marks, D., Uderman, J.Z., & Chimiklis, A. (2013). Cogmed working memory training for youth with ADHD: A closer examination of efficacy utilizing evidence-based criteria. *Journal of Clinical Child & Adolescent Psychology, 42*, 769-783.
- Cornhill, H., & Case-Smith, J. (1996). Factors that relate to good and poor handwriting. *The American Journal of Occupational Therapy, 50*, 732-739.
- Durand, M., Hulme, C., Larkin, R., & Snowling, M. (2005). The cognitive foundations of reading and arithmetic skills in 7- to 10-year-olds. *Journal of Experimental Child Psychology, 91*, 113-136.
- Efron, B., & Tibshirani, R. (1993). *An introduction to the bootstrap*. New York: Chapman & Hall/CRC.
- Frazier, T.W., Demaree, H.A., & Youngstrom, E.A. (2004). Meta-analysis of intellectual and neuropsychological test performance in Attention-deficit/Hyperactivity Disorder. *Neuropsychology, 18*, 543-555.
- Fritz, M.S., & MacKinnon, D.P. (2007). Required sample size to detect the mediated effect. *Psychological Science, 18*, 233-239.
- Gadow, K.D., Sprafkin, J., & Salisbury, H. (2004). Further validity evidence for the teacher version of the Child Symptom Inventory-4. *School Psychology Quarterly, 19*, 50-71.
- Ganis, G., Thompson, W.L., & Kosslyn, S.M. (2004). Brain areas underlying visual mental imagery and visual perception: An fMRI study. *Cognitive Brain Research, 20*, 226-241.
- Gathercole, S.E., Alloway, T.P., Willis, C., & Adams, A. (2006). Working memory in children with reading disabilities. *Journal of Experimental Child Psychology, 93*, 265-281.

- Gathercole, S.E., Brown, L., & Pickering, S.J. (2003). Working memory assessments at school entry as longitudinal predictors of National Curriculum attainment levels. *Educational and Child Psychology, 20*, 109-122.
- Gathercole, S.E., Pickering, S.J., Knight, C., & Stegmann, Z. (2004). Working memory skills and educational attainment: Evidence from national curriculum assessments at 7 and 14 years of age. *Applied Cognitive Psychology, 18*, 1–16.
- Gibson, B.S., Gondoli, D.M., Johnson, A.C., Steeger, C.M., Dobrzanski, B.A., & Morrissey, R.A. (2011). Component analysis of verbal versus spatial working memory training in adolescents with ADHD: A randomized, controlled trial. *Child Neuropsychology, 17*, 546-563.
- Gomez, R., & Sanson, A.V. (1994). Effects of experimenter and mother presence on the attentional performance and activity of hyperactive boys. *Journal of Abnormal Child Psychology, 22*, 517-529.
- Hayes, A.F. (2009). Beyond Baron and Kenny: Statistical mediation analysis in the new millennium. *Communication Monographs, 76*, 408–420.
- Hayes, A.F. (2013). Introduction to mediation, moderation, and conditional process analysis: A regression-based approach. Guilford Press.
- Hervey, A.S., Epstein, J.N., Curry, J.F., Tonev, S., Eugene Arnold, L., Keith Conners, C., ... & Hechtman, L. (2006). Reaction time distribution analysis of neuropsychological performance in an ADHD sample. *Child Neuropsychology, 12*, 125-140.
- Hinshaw, S.P. (1992). Externalizing behavior problems and academic underachievement in childhood and adolescence: Causal relationships and underlying mechanisms. *Psychological Bulletin, 111*, 127-155.

- Holmes, J., Gathercole, S.E., Place, M., Alloway, T.P., Elliott, J.G., & Hilton, K.A. (2010). The diagnostic utility of executive function assessments in the identification of ADHD in children. *Child and Adolescent Mental Health, 15*, 37–43.
- Houdé, O., Rossi, S., Lubin, A., & Joliot, M. (2010). Mapping numerical processing, reading, and executive functions in the developing brain: An fMRI meta-analysis of 52 studies including 842 children. *Developmental Science, 13*, 876-885.
- Huang-Pollock, C.L., Karalunas, S.L., Tam, H., & Moore, A.N. (2012). Evaluating vigilance deficits in ADHD: A meta-analysis of CPT performance. *Journal of Abnormal Psychology, 121*, 360-371.
- Jacobson, L.A., Ryan, M., Martin, R.B., Ewen, J., Mostofsky, S.H., Denckla, M.B., & Mahone, E.M. (2011). Working memory influences processing speed and reading fluency in ADHD. *Child Neuropsychology, 17*, 209-224.
- Jonides, J., Schumacher, E.H., Smith, E.E., Koeppe, R.A., Awh, E., Reuter-Lorenz, P.A., ... & Willis, C.R. (1998). The role of parietal cortex in verbal working memory. *The Journal of Neuroscience, 18(13)*, 5026-5034.
- Karalunas, S.L., Geurts, H.M., Konrad, K., Bender, S., & Nigg, J.T. (2014). Reaction time variability in ADHD and autism spectrum disorders: Measurement and mechanisms of a proposed trans-diagnostic phenotype. *Journal of Child Psychology and Psychiatry, 55*, 685-710.
- Karalunas, S.L., & Huang-Pollock, C.L. (2013). Integrating impairments in reaction time and executive function using a diffusion model framework. *Journal of Abnormal Child Psychology, 41*, 837-850.

- Karalunas, S.L., Huang-Pollock, C.L., & Nigg, J.T. (2012). Decomposing attention-deficit/hyperactivity disorder (ADHD)-related effects in response speed and variability. *Neuropsychology, 26*, 684-694.
- Kasper, L.J., Alderson, R.M., & Hudec, K.L. (2012). Moderators of working memory deficits in children with attention-deficit/hyperactivity disorder (ADHD): A meta-analytic review. *Clinical Psychology Review, 32*, 605-617.
- Kaufman, J., Birmaher, B., Brent, D., Rao, U., Flynn, C., Moreci, P... Ryan, N. (1997). Schedule for affective disorders and schizophrenia for school-age children-present and lifetime version (K-SADS-PL): Initial reliability and validity data. *Journal of the American Academy of Child and Adolescent Psychiatry, 36*, 980-988.
- Kofler, M.J., Alderson, R.M., Raiker, J.S., Bolden, J., Sarver, D.E., & Rapport, M.D. (2014). Working memory and intraindividual variability as neurocognitive indicators in ADHD: Examining competing model predictions. *Neuropsychology, 28*, 459-471.
- Kofler, M.J., Rapport, M.D., Bolden, J., Sarver, D.E., & Raiker, J.S. (2010). ADHD and working memory: The impact of central executive deficits and exceeding storage/rehearsal capacity on observed inattentive behavior. *Journal of Abnormal Child Psychology, 38*, 149-161.
- Kofler, M.J., Rapport, M.D., Sarver, D.E., Raiker, J.S., Orban, S.A., Friedman, L.M., & Kolomeyer, E.G. (2013). Reaction time variability in ADHD: A meta-analytic review of 319 studies. *Clinical psychology review, 33*, 795-811.
- Lawrence, V., Houghton, S., Douglas, G., Durkin, K., Whiting, K., & Tannock, R. (2004). Executive function and ADHD: A comparison of children's performance during neuropsychological testing and real-world activities. *Journal of Attention Disorders, 7*, 137-149.

- Li, J.J., Cutting, L.E., Ryan, M., Zilioli, M., Denckla, M.B., & Mahone, M.E. (2009). Response variability in rapid automatized naming predicts reading comprehension. *Journal of Clinical and Experimental Neuropsychology*, *31*, 877-888.
- Martinussen, R., Hayden, J., Hogg-Johnson, S., & Tannock, R. (2005). A meta-analysis of working memory impairments in children with attention-deficit/hyperactivity disorder. *Journal of the American Academy of Child and Adolescent Psychiatry*, *44*, 377–384.
- Martinussen, R., & Tannock, R. (2006). Working memory impairments in children with attention-deficit hyperactivity disorder with and without comorbid language learning disorders. *Journal of Clinical and Experimental Neuropsychology*, *28*, 1073-1094.
- McGrath, L.M., Pennington, B.F., Shanahan, M.A., Santerre-Lemmon, L.E., Barnard, H.D., Willcutt, E.G...Olson, R.K. (2011). A multiple deficit model of reading disability and attention-deficit/hyperactivity disorder: Searching for shared cognitive deficits. *The Journal of Child Psychology and Psychiatry*, *52*, 547-557.
- Meyer, M.L., Salimpoor, V.N., Wu, S.S., Geary, D.C., & Menon, V. (2010). Differential contribution of specific working memory components to mathematics achievement in 2nd and 3rd graders. *Learning and Individual Differences*, *20*, 101–109.
- Montgomery, J.W. (1995). Sentence comprehension in children with specific language impairment: The role of phonological working memory. *Journal of Speech and Hearing Research*, *38*, 187-199.
- Nigg, J.T. (2005). Neuropsychologic theory and findings in attention-deficit/hyperactivity disorder: The state of the field and salient challenges for the coming decade. *Biological Psychiatry*, *57*, 1424-1435.

- Power, T.J. (1992). Contextual factors in vigilance testing of children with ADHD. *Journal of Abnormal Child Psychology*, 20, 579-593.
- Price, C.J., & Devlin, J.T. (2003). The myth of the visual word form area. *Neuroimage*, 19, 473-481.
- Raiker, J.S., Rapport, M.D., Kofler, M.J., & Sarver, D.E. (2012). Objectively-measured impulsivity and attention-deficit/hyperactivity disorder (ADHD): Testing competing predictions from the working memory and behavioral inhibition models of ADHD. *Journal of Abnormal Child Psychology*, 40, 699-713.
- Rapport, M.D., Alderson, R.M., Kofler, M.J., Sarver, D.E., Bolden, J., & Sims, V. (2008). Working memory deficits in boys with attention-deficit/hyperactivity disorder (ADHD): The contribution of central executive and subsystem processes. *Journal of Abnormal Child Psychology*, 36, 825–837.
- Rapport, M.D., Bolden, J., Kofler, M.J., Sarver, D.E., Raiker, J.S., & Alderson, R.M. (2009). Hyperactivity in boys with attention deficit/hyperactivity disorder (ADHD): A ubiquitous core symptom or manifestation of working memory deficits? *Journal of Abnormal Child Psychology*, 37, 521–534.
- Rapport, M.D., Kofler, M.J., Alderson, R.M., & Raiker, J. (2008). Attention-deficit/hyperactivity disorder. In M. Hersen & D.Reitman (Eds.), *Handbook of psychological assessment, case conceptualization and treatment, volume 2: Children and adolescents* (pp. 125–157). NJ: Wiley & Sons.
- Rapport, M.D., Orban, S.A., Kofler, M.J., & Friedman, L.M. (2013). Do programs designed to train working memory, other executive functions, and attention benefit children with ADHD? A

- meta-analytic review of cognitive, academic, and behavioral outcomes. *Clinical Psychology Review*, 33, 1237-1252.
- Rappport, M.D., Scanlan, S.W., & Denney, C.B. (1999). Attention-deficit/hyperactivity disorder and scholastic achievement: A model of dual developmental pathways. *Journal of Child Psychology and Psychiatry*, 40, 1169-1183.
- Rubia, K., Alegria, A.A., Cubillo, A.I., Smith, A.B., Brammer, M.J., & Radua, J. (2013). Effects of stimulants on brain function in attention-deficit/hyperactivity disorder: A systematic review and meta-analysis. *Biological Psychiatry*. (ahead-of-print), 1-13.
- Rucklidge, J.J., & Tannock, R. (2002). Neuropsychological profiles of adolescents with ADHD: Effects of reading difficulties and gender. *Journal of Child Psychology and Psychiatry*, 43, 988-1003.
- Sarver, D.E., Rappport, M.D., Kofler, M.J., Scanlan, S.W., Raiker, J.S., Altro, T.A., & Bolden, J. (2012). Attention problems, phonological short-term memory, and visuospatial short-term memory: Differential effects on near-and long-term scholastic achievement. *Learning and Individual Differences*, 22, 8-19.
- Schumacher, E.H., Lauber, E., Awh, E., Jonides, J., Smith, E.E., & Koeppel, R.A. (1996). PET evidence for an amodal verbal working memory system. *Neuroimage*, 3, 79-88.
- Semrud-Clikeman, M., Biederman, J., Sprich-Buckminster, S., Lehman, B.K., Faraone, S.V., & Norman, D. (1992). Comorbidity between ADDH and learning disability: A review and report

- in a clinically referred sample. *Journal of the American Academy of Child & Adolescent Psychiatry*, 31, 439-448.
- Semrud-Clikeman, M., Guy, K., Griffin, J.D., & Hynd, G.W. (2000). Rapid naming deficits in children and adolescents with reading disabilities and attention deficit hyperactivity disorder. *Brain and Language*, 74, 70-83.
- Sergeant, J.A., Geurts, H., & Oosterlaan, J. (2002). How specific is a deficit of executive functioning for Attention-Deficit/Hyperactivity Disorder? *Behavioural Brain Research*, 130, 3-28.
- Sergeant, J.A., & Scholten, C.A. (1985). On data limitations in hyperactivity. *Journal of Child Psychology and Psychiatry*, 26, 111–124.
- Shanahan, M.A., Pennington, B.F., Yerys, B.E., Scott, A., Boada, R., Willcutt, E.G...DeFries, J.C. (2006). Processing speed deficits in Attention deficit/hyperactivity disorder and Reading Disability. *Journal of Abnormal Child Psychology*, 34, 585-602.
- Shaw, P., Eckstrand, K., Sharp, W., Blumenthal, J., Lerch, J. P., Greenstein, D., & Rapoport, J. L. (2007). Attention-deficit/hyperactivity disorder is characterized by a delay in cortical maturation. *Proceedings of the National Academy of Sciences USA*, 104, 19649–19654
- Shipstead, Z., Redick, T., & Engle, R.W. (2012). Is working memory training effective? *Psychological Bulletin*, 138, 628-654.
- Shrout, P.E., & Bolger, N. (2002). Mediation in experimental and nonexperimental studies: New procedures and recommendations. *Psychological Methods*, 7, 422–445.
- Snyder, H.R. (2013). Major depressive disorder is associated with broad impairments on neuropsychological measures of executive function: A meta-analysis and review. *Psychological Bulletin*, 139, 81-132.

- Sonuga-Barke, E., Bitsakou, P., & Thompson, M. (2010). Beyond the dual pathway model: Evidence for the dissociation of timing, inhibitory, and delay-related impairments in attention-deficit/hyperactivity disorder. *Journal of the American Academy of Child & Adolescent Psychiatry, 49*, 345-355.
- Swanson, H.L., & Howell, M. (2001). Working memory, short-term memory, and speech rate as predictors of children's reading performance at different ages. *Journal of Educational Psychology, 93*, 720-734.
- Swanson, L., & Kim, K. (2007). Working memory, short-term memory, and naming speed as predictors of children's mathematical performance. *Intelligence, 35*, 151-168.
- Tabachnick, B.G., & Fidell, L.S. (2007) *Using multivariate statistics (5th ed.)*. Boston: Allyn & Bacon/Pearson Education.
- Tan, L., Laird, A.R., Li, K., & Fox, P.T. (2005). Neuroanatomical correlates of phonological processing of Chinese characters and alphabetic words: A meta-analysis. *Human Brain Mapping, 25*, 83-91.
- Tannock, R., Martinussen, R., & Frijters, J. (2000). Naming speed performance and stimulant effects indicate effortful, semantic processing deficits in attention-deficit/hyperactivity disorder. *Journal of Abnormal Child Psychology, 28*, 237-252.
- Wager, T.D., & Smith, E.E. (2003). Neuroimaging studies of working memory. *Cognitive, Affective, & Behavioral Neuroscience, 3*, 255-274.
- Wechsler, D. (2003). *Wechsler intelligence scale for children—fourth edition*. San Antonio: Psychological Corporation.

Willcutt, E.G., Doyle, A.E., Nigg, J.T., Faraone, S.V., & Pennington, B.F. (2005). Validity of the executive function theory of attention-deficit/hyperactivity disorder: A meta-analytic review. *Biological Psychiatry, 57*, 1336–1346.

Willcutt, E.G., & Pennington, B.F. (2000). Psychiatric comorbidity in children and adolescents with reading disability. *Journal of Child Psychology and Psychiatry, 41*, 1039-1048.

Wodka, E.L., Loftis, C., Mostofsky, S.H., Prahme, C., Larson, J.C.G., Denckla, M.B., & Mahone, M.E. (2008). Prediction of ADHD in boys and girls using the D-KEFS. *Archives of Clinical Neuropsychology, 23*, 283-293.