WORKING MEMORY AND MOTOR ACTIVITY IN CHILDREN WITH ADHD: DOES STIMULUS PRESENTATION MODALITY MATTER?

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Abstract: Empirical support for the functional relationship between working memory (WM) and motor activity is well established for children with attention-deficit/hyperactivity disorder (ADHD) and typically developing (TD) children. The episodic buffer component of WM, however, has been subject to few empirical investigations in children, and only once examined with respect to the functional relationship between WM demands and motor activity. Motor activity of forty-two children (ADHD = 23, TD = 19) aged 8 to 12 years was recorded while they were administered three versions of a phonological WM task that varied with regard to stimulus presentation modality (auditory, visual, or dual auditory and visual), as well as a visuospatial task and a control task. Mixed model analyses of variance indicated that children's WM performance varied according to stimulus presentation modality and that activity remained relatively stable across tasks. Further examination indicated that motor activity changes were influenced primarily by changes in central executive demands across tasks. Overall, findings suggest that episodic buffer processes (elicited via dual modality presentation of verbal stimuli- information that is processed via a visual and verbal code) benefits WM performance but does not appear to impact motor activity above and beyond the contribution of central executive demands.

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CHAPTER I

INTRODUCTION

Hyperactivity is one of the primary referral reasons of children with ADHD (Gaub & Carlson, 1997; Barkley, 2014) and is significantly correlated with poor social-decision making (Humphreys, Galán, Tottenham, & Lee, 2016), later academic underachievement (Fergusson, Lynskey, & Horwood, 1997), and adult criminal activity (Babinski, Hartsough, & Lambert, 1999). Attempts to explicate mechanistic underpinnings of attention-deficit/hyperactivity disorder (ADHD) have led to a number of models with varying predictions of ADHD-related hyperactivity. For example, inhibition-centric models predict ubiquitous hyperactivity that results from failure to withhold or stop prepotent responses and/or aversion to pre-reinforcement delays (Barkley, 1997; Sonuga-Barke, Bitsakou, & Thompson, 2010). The functional working memory (WM) model of ADHD, in contrast, suggests abnormal neurobiological substrates such as cortical underarousal and under-developed frontal/prefrontal regions lead to working memory impairments in children with the disorder (Rapport, Chung, Shore, & Isaacs, 2001; Rapport, Alderson, Kofler, Sarver, Bolden, & Sims, 2008; Rapport, Bolden, Kofler, Sarver, Raiker, & Alderson, 2009). Further, the model suggests that hyperactivity serves as a compensatory mechanism to improve dopamine production and autonomic arousal needed to meet WM demands in the environment (Rapport et al., 2009).

Rapport and colleagues' (2001) functional WM model of ADHD is based on Baddeley's (Baddeley & Hitch, 1974; Baddeley, 2007) multi-component WM model, which defines working memory as a limited capacity, temporary information store that allows for maintenance, manipulation, and storage of mental information. Storage, rehearsal, and processing of phonological and visuospatial information is allocated to anatomically (Smith, Jonides, & Koeppe, 1996; Fassbender & Schweitzer, 2006) and functionally (Baddeley, 2003) separate subsystems, while a domain-general central executive is responsible for allocation of resources to the phonological and visuospatial subsystems, simultaneous information processing, interference control (i.e., limiting the access of extraneous information to WM), reordering, updating, and the division, switching, and maintenance of controlled-focused attention (Baddeley, 2007). Lastly, the model describes an episodic buffer that serves as a passive store of bound information from perception, long-term memory, and discrete visuospatial and phonological subsystems (Baddeley, 2012). Importantly, the episodic buffer accounts for evidence of ancillary storage capacity supplementary to the discrete phonological and visuospatial subsystems (Baddeley, 2007). For example, the episodic buffer appears to augment digit span performance, such that limiting access of stimuli representations to the phonological loop via articulatory suppression has less impact than what would be expected if only the phonological loop was involved (Baddeley, 2007; Larsen & Baddeley, 2003). Similarly, findings from studies of patients with short-term memory deficits reveal that they are able to recall approximately four times more digits when the phonological information is presented visually (Shallice & Warrington, 1970; Basso et al., 1982).

Extant experimental and meta-analytic research has revealed moderate to large-magnitude ADHD deficits in phonological storage/rehearsal processes, medium to large ADHD deficits in visuospatial storage/rehearsal processes, and moderate to large-magnitude (i.e., 0.43 to 3.76 standard deviation units) ADHD-related central executive deficits (Alderson, Rapport, Hudec, Sarver, & Kofler, 2010; Friedman, Rapport, Raiker, Orban, & Eckrich, 2017; Kasper, Alderson, & Hudec, 2012; Martinussen, Hayden, Hogg-Johnson, & Tannock, 2005; Rapport et al., 2008). A competing model of the disorder argues that WM deficits, along with other impairments of neurocognitive functioning, serve to moderate ADHD symptom severity but are not central to the disorder (Halperin & Schulz, 2006). Development of this model largely stems from select study findings that suggest approximately 50% or fewer participants with ADHD evinced WM deficits (Lambek, Tannock, Dalsgaard, Trillingsgaard, Damm, & Thomsen, 2011; Martinussen et al., 2005; Willcutt, Doyle, Nigg, Faraone, & Pennington, 2005). Meta-analytic moderation analyses identifying best-case procedures in methodological and sample characteristics, however, suggest that 98% of children with ADHD are expected to exhibit WM deficits relative to their TD peers (Kasper et al., 2012). Moreover, Tarle et al. (2017) systematically manipulated variation in central executive WM demands, administration procedures (use or disuse of discontinue rules), and scoring methods (partial vs absolute) – a procedure that served as an analogue to methodological heterogeneity common across studies of ADHD and WM – and found that the magnitude of ADHD-related WM deficits (and percent of children detected to have WM impairments) significantly varied depending on methodology (Tarle, Alderson, Patros, Lea, Hudec, & Arrington, 2017).

Although extensive research has examined phonological storage/rehearsal, visuospatial storage/rehearsal, and central executive deficits in children with ADHD, only two studies to date have investigated potential episodic buffer deficits (Alderson, Patros, Tarle, Hudec, Kasper, & Lea, 2015; Kofler, Spiegel, Austin, Irwin, Soto, & Sarver, 2018). The first study presented children with and without ADHD three conditions of a phonological working memory task that varied with regard to stimulus presentation modality (auditory, visual, or dual auditory/visual). Unimodal-auditory presentation of phonological stimuli yielded the largest magnitude WM deficit in the ADHD group. Moreover, although children with ADHD exhibited improved performance during visual and dual modality conditions, their performance remained significantly below the performance of TD children. In contrast, TD children did not exhibit performance differences between the auditory and visual phonological conditions, but recalled significantly more stimuli during the dual phonological condition. Collectively, Alderson and colleagues concluded that children with ADHD did not benefit from multimodal binding (i.e., the binding of visually and verbally presented information) via episodic buffer processes to the same extent as their TD peers (Alderson et al., 2015). A more recent study examined episodic buffer functioning (bound phonological and visuospatial information) in a group of children with ADHD and a non-ADHD control group (Kofler et al., 2018) and found that the performance of both groups of children decreased during the episodic buffer condition, relative to the unimodal phonological and visuospatial conditions, contrasting findings from Alderson et al. (2015).

Extant investigations have also yielded strong evidence for Rapport et al.'s (2001, 2008, 2009) prediction of a functional/causal relationship between WM demands and ADHD related motor activity. Rapport and colleagues' seminal study provided the first experimental evidence of this link, demonstrating large-magnitude increased in ADHD-related hyperactivity as a result of central executive demand (Rapport et al., 2009). Subsequent studies have documented that processes associated with controlled focus of attention, and not behavioral disinhibition, accounted for increases in motor activity in children with ADHD (Alderson, Rapport, Kasper, Sarver, & Kofler, 2012), and that increased ADHD-related hyperactivity is specifically associated with increased WM demands and not just non-specific, non-executive functions (Hudec, Alderson, Patros, Lea, Tarle, & Kasper, 2015). Similarly, findings from Patros and colleagues (2017) indicated that ADHD-related hyperactivity exhibited during a self-control task was attributable to WM processes rather than deficits of self-control (Patros, Alderson, Hudec, Tarle, & Lea, 2017). Directly linking performance and activity, Hartanto and colleagues found that children with ADHD display greater activity during correct, but not incorrect, trials of a cognitive control task (Hartanto, Krafft, Iosif, & Schweitzer, 2016), while Sarver and colleagues (2016) similarly found a relationship between increased activity and WM performance when experimental tasks were rank ordered by increasing activity (Sarver, Rapport, Kofler, Raiker, & Friedman, 2015). Finally, a recent comprehensive meta-analytic review has provided strong support for the functional relationship between ADHD-related motor activity and environmental demands, with markedly greater between-group (ADHD relative to TD) effect sizes found in conditions with higher working memory demands (Kofler, Raiker, Sarver, Wells, & Soto, 2016).

To date, only one study has examined the relationship between episodic buffer demands and motor activity in children with and without ADHD (Kofler et al., 2018). Overall, both children with ADHD and children in a non-ADHD control group exhibited similar increases in motor activity during the episodic buffer condition compared to a low WM demand control condition. Moreover, the groups' lower motor activity during the episodic buffer condition was attributed to central executive demands rather than episodic buffer functioning (Kofler et al., 2018). Conclusions from the study should be tempered, however, as data from the ADHD sample were compared to a heterogeneous sample of children with non-ADHD psychiatric disorders (38%) and neurotypical children (Kofler et al., 2018). That is, it is not clear which population Kofler and colleague's control group represents, and consequently, potential inferences about the relationship between episodic buffer demands and motor activity in the greater population of children with ADHD are obscured. That is, a similar study with well-defined samples of typically developing children and children with ADHD may yield entirely different results.

The current study examined the effect of the episodic buffer on motor activity in well-defined samples of children with ADHD and TD children. Motor activity was objectively measured via three high precision actigraphs during a control condition that placed minimal demands on WM and during tasks that placed high demands on phonological WM. Three phonological working memory tasks presented stimuli via auditory, visual, or dual presentation. The phonological auditory condition provided a purely unimodal index of phonological storage/rehearsal processes. The phonological visual condition, in contrast, was hypothesized to provide an index of phonological storage/rehearsal, the conversion of visual text (letters) to phonological information (i.e., orthographic to phonological conversion), and/or potential multimodal binding (i.e., binding of visually encoded phonological information). The phonological dual condition encompassed all characteristics of the phonological auditory and phonological visual tasks, which consequently served as methodological controls. Specifically, it was hypothesized that differences between the phonological dual condition and the other phonological conditions would provide the most compelling evidence of episodic buffer processes. Finally, a visuospatial WM task was included as a visuospatial analogue to the phonological tasks and to yield more nuanced information about ADHD-related WM impairments across different stimuli and presentation modalities.

Significant effects of group, WM condition, and the interaction between group and condition on WM performance were expected. Children with ADHD were expected to exhibit disproportionately lower WM performance during the phonological auditory condition relative to the phonological visual and phonological dual conditions. Performance for both groups was expected to be highest during the phonological dual condition, followed by the phonological visual, phonological auditory, and visuospatial conditions. These predictions were based on previous experimental (Alderson et al., 2015; Rapport et al., 2008) and meta-analytic (Kasper et al., 2012; Martinussen et al., 2005; Willcutt et al., 2005) investigations. Children with ADHD were expected to exhibit disproportionately greater motor activity during the WM conditions (phonological auditory, phonological visual, phonological dual, visuospatial) relative to the control conditions. In addition, children with ADHD were expected to exhibit significantly greater motor activity during the phonological auditory condition relative to the phonological visual and phonological dual conditions and to exhibit the lowest activity during the visuospatial condition, while TD children were expected to be most active during the phonological auditory and phonological visual conditions relative to the phonological dual and visuospatial conditions. These predictions were based on previous findings of the relationship between WM demands and motor activity (Hudec et al., 2015; Patros et al., 2017; Rapport et al., 2009), as well as an integration of previous research on WM performance (Alderson et al., 2015) and predictions from the functional working memory model (i.e., motor activity increases as a function of WM demand; Rapport et al., 2008).

CHAPTER II

METHOD

Participants

Participants were typically developing children and children with ADHD aged 8-12 years, recruited by the Center for Research of Attention and Behavior (CRAB). Participants were recruited from the community via fliers in local businesses, word of mouth, and through the Psychological Services Center (PSC), a university-based mental health clinic. Parental consent and child assent was obtained prior to participation, and the Institutional Review Board (IRB) approved the study prior to data collection. Children were grouped as TD or as ADHD based on the results of an evaluation consisting of well-established, reliable, and valid behavior rating scales completed by parents and teachers, cognitive and achievement testing, and clinical interviews. In exchange for participation, parents of children were provided with comprehensive psychoeducational reports from the child's evaluation.

Group Assignment

To be included in the ADHD group, children met the following criteria: (1) a diagnosis by the Center for Research of Attention and Behavior's directing clinical psychologist based on DSM-5 (APA, 2013) criteria for an ADHD, Combined presentation, supplemented by information provided by parents on the K-SADS-PL semi-structured clinical interview, (2) parent ratings at least 1.5 standard deviations (i.e., within the clinical range) greater than the mean on either of the ADHD DSM-5 Symptom Scales of the Conners-3P[1] or at least 2 standard deviations greater than the mean on the ADHD Problems DSM-Oriented Scale of the CBCL, and (3) teacher ratings at least 1.5 standard deviations (i.e., within the clinical range) greater than the mean on either of the ADHD DSM-5 Symptom Scales of the Conners-3T or at least 2 standard deviations greater than the mean on the ADHD Problems DSM-Oriented Scale of the TRF. The majority (87%) of children in the ADHD group were also diagnosed with comorbid disorders, including oppositional defiant disorder (n = 11), specific learning disorder (n = 3), enuresis (n = 3), encopresis (n = 2), conduct disorder (n = 1), specific phobia (n = 1), disruptive mood dysregulation disorder (n = 1), and major depressive disorder (n = 1). Children with comorbid disorders were not excluded from the ADHD group to increase the generalizability of findings, as the majority of children with ADHD have at least one other comorbid diagnosis (Wilens et al., 2002). Twenty-three children (one girl) were included in the ADHD group.

To be included in the TD group, children met the following criteria: (1) no diagnosis by the Center for Research of Attention and Behavior's directing clinical psychologist based on DSM-5 (APA, 2013) criteria, evidenced by information provided by parents on the K-SADS-PL semi-structured clinical interview, (2) a normal developmental history based on information provided by the parent during a psychosocial interview, (3) ratings less than 1.5 standard deviations above the mean (i.e., within the normal range) on all scales

[1] Parent and teacher ratings on the Conners 3 were not available for one child in the ADHD group; the Conners' Rating Scales-Revised, Long, was used instead. Parent and teacher ratings were in the clinical range for both the DSM-IV Inattentive and DSM-IV Hyperactive-Impulsive scales.

of the Conners-3P[2], the Conners-3T, the CBCL, and the TRF and (4) ratings less than 1.5 standard deviations above the mean (i.e., within the normal range) on the clinical scales of the CDI and RCMAS-2. Nineteen children (two girls) were included in the TD group.

Parents of participating children were asked to have the children discontinue the use of any psychostimulant medication 24 hours prior to research sessions. Children presenting with (1) gross neurological, sensory, or motor impairment, (2) history of seizure disorder, (3) psychosis, and/or a (4) a *Wechsler Intelligence Scale for Children* (WISC) *Fourth* (Wechsler, 2003) or *Fifth* (Wechsler, 2014) edition Full Scale IQ (FSIQ) score less than 80 were excluded from the study.

Measures

Psychosocial and clinical interviews. A psychosocial interview was administered to parents of participants to assess pregnancy history (pre, peri, post), developmental history, medical history, educational history, family history, and current social functioning. Information from this interview was integrated with other interview and rating scale data in order to best determine the presence or absence of any diagnosis(es) in accordance with DSM-5 diagnostic criteria. Information from this interview was also incorporated into the comprehensive psychoeducational report provided to parents of participants.

The *Kiddie Schedule for Affective Disorders and Schizophrenia Present and Lifetime Version (K-SADS-PL)* was used to assess onset, course, frequency, severity, and duration of symptoms linked to various affective, psychotic, anxiety, behavioral, and

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[2] Parent Ratings for two children in the TD group were elevated on the ADHD Predominately Hyperactive-Impulsive scale of the Conners 3 (T = 69, T = 65). Follow-up interviews with the parents indicated that in one case, the behaviors were related to a recent stressor and in the other case, they were reflective of a single specific behavior (i.e., not a cluster of symptoms). In neither case was there any evidence of impairment.

substance abuse disorders based on DSM-5 diagnostic criteria. This semi-structured clinical interview has strong psychometric properties. Test-retest reliability for current diagnoses ranges from acceptable to excellent (k = .63 to 1.00; Kaufman et al., 1997). The K-SADS-PL has good overall convergent and discriminant validity with other measures of behavioral and psychiatric disorders (e.g., Early Childhood Inventory-4 and Child Behavior Checklist; Birmaher, et al., 2009; Pelham, Fabiano, & Massetti, 2005).

Behavior rating scales. To assess child functioning across situations, and consistent with the gold-standard for ADHD assessment (Gualtieri & Johnson, 2005), broad and narrow-band rating scales from multiple reporters (parent and teacher) were used to inform the diagnostic process.

***Child Behavior Checklist and Teacher Report Form*.** The *Child Behavior Checklist* (CBCL) and *Teacher's Report Form* (TRF) provide age-normed ratings of children's emotional and behavioral functioning (Achenbach, & Rescorla, 2001). The CBCL and TRF provide two broadband dimensions (internalizing and externalizing) and 8 narrow-band clinical domain scores (e.g., rule-breaking behavior, aggressive behavior, anxious/depressed, withdrawn/ depressed, somatic complaints), as well as clinical DSM-oriented scales that correlate with symptoms of disorders found in the *Diagnostic and Statistical Manual for Mental Disorders, 4th edition* (DSM-IV). Additionally, the Attention Problems syndrome and DSM-oriented scales on the TRF are further subdivided into Inattention and Hyperactivity-Impulsivity subscales. Test-retest reliability ranges from good to excellent across the CBCL (α = .82-.94) subscales, and ranges from adequate to excellent across TRF subscales (α = .60-.96; Achenbach & Rescorla, 2001). Internal consistency ranges from fair to excellent across the CBCL (α =

.78-.97) and TRF (α = .72-.97; Achenbach & Rescorla, 2001) subscales. In previous studies, the CBCL has discriminated between ADHD subtypes (Ostrander, Weinfurt, Yarnold, & August, 1998) and has strong construct validity (Biederman et al., 1995).

Conners 3 Parent and Teacher Rating Scales. The Conners 3- Parent (C3-P) and Conners 3- Teacher (C3-T) are narrow band measures designed to assess externalizing behaviors in children aged 6-18 years. The measures provide six content scales and four DSM-5 oriented scales. The Conners 3 also provides validity scales that indicate whether the responses suggest a positive impression, negative impression, or inconsistency index. An ADHD Index Score provides a measure of how strongly a classification of ADHD is indicated, and 3 Global Index Scores summarize measures of emotional and behavioral ratings. Internal consistency of the C3-P and the C3-T ranges from very good to excellent (α = .77-.97), and both measures have high test-retest reliability (r = .71-.98) and good convergent validity (Conners, 2008).

Children's Depression Inventory. Children completed the *Children's Depression Inventory* (CDI; Kovacs, 2003), a 27-item self-report measure, to assess for depression-related symptoms. The CDI is appropriate for use in children aged 7 to 17 and has adequate internal consistency for each of its five scales (negative mood, interpersonal problems, ineffectiveness, anhedonia, and negative self-esteem; α = .59-.68; Kovacs, 2003). Further, extant research on the CDI has demonstrated strong discriminative and concurrent validity (Kovacs, 2003).

Revised Children's Manifest Anxiety Scale-2. Children completed the *Revised Children's Manifest Anxiety Scale-II* (RCMAS-2; Reynolds, & Richmond, 2008) to assess for anxiety-related symptoms. The RCMAS-2 is a 49-item self-report measure for children aged 6 to 19, and measures three areas of functioning: physiological anxiety, worry, and social anxiety. The measure also includes two validity scales, one for social desirability (defensiveness), and another to detect biased responding and validity (inconsistent responding index). The RCMAS-2 has outstanding internal consistency for the Total Anxiety scale ($\alpha = .92$), and good to excellent internal inconsistency for the subscales ($\alpha = .75$-.86; Reynolds & Richmond, 2008). One-week test-retest reliability ranges from adequate to good ($\alpha = .64$-.76; Reynolds & Richmond, 2008) across the Total Anxiety scale and the subscales. The RCMAS-2 evinces good construct validity (Reynolds & Richmond, 2008)

Intellectual and Academic Functioning

Wechsler Intelligence Scale for Children. Children were administered all subtests of the *Wechsler Intelligence Scale for Children* (WISC) *Fourth* (Wechsler, 2003) or *Fifth* (Wechsler, 2014) edition to assess current intellectual functioning. The WISC-V has outstanding psychometric properties including high internal consistency, test-retest reliability, content validity, criterion validity, and construct validity (Wechsler, 2014). The WISC was used to determine study inclusion (FSIQ > 80).

Kaufman Test of Educational Achievement. Children were administered all subtests of the *Kaufman Test of Educational Achievement* (KTEA) *Second* (Kaufman, 2004) or *Third* edition (Kaufman & Kaufman, 2014) to measure current academic achievement and to confirm that children would be able to understand the tasks administered during research sessions. The KTEA-3 evinces strong psychometric properties, with composite score reliability ranging from good to excellent ($\alpha = .92$-.99), with the exception of Oral Fluency (α = .70-.74; Kaufman & Kaufman, 2014). The KTEA-3 has strong content and construct validity (Kaufman & Kaufman, 2014).

Experimental Tasks

Phonological working memory task. A phonological working memory task (Rapport et al., 2008), was used to measure children's phonological working memory. The phonological working memory task requires participants to re-order a jumbled series of single digit numbers and one letter, similar to the Letter-Number Sequencing subtest of the WISC-V (Weschler, 2014). Children were instructed to rearrange and say the numbers in order from least to greatest and say the letter last (see Figure 1). Participants used a touch-screen computer (37 x 30 cm monitor screen) to complete the task, which was programmed using SuperLab Pro 4.0 (Cedrus, San Pedro, CA) software.

The phonological working memory task was presented via three modality conditions (auditory, visual, and dual), each with four set size blocks consisting of 24 trials each. Stimuli were presented in counterbalanced order (determined using a Latin Square design) to control for possible order effects. For the phonological auditory condition, stimuli were presented through the computer's speakers. In the visual condition, stimuli were successively presented on the computer screen. The stimuli measure 5.1 cm high and all letters are capitalized in bold, size 200, Times New Roman font. In the dual condition, stimuli were simultaneously presented verbally and visually.

The letter was never presented first or last within each trial in order to decrease the likelihood of primacy or recency effects. Additionally, no stimulus was presented twice in the same trial. Each stimulus was presented for 800 ms, followed by a 200 ms inter-stimulus interval. Following the presentation of the final stimulus within a trial, an auditory “click” sounded and a green traffic light appeared on the screen to prompt the children to verbally respond. Following their response, children were to touch the screen to advance to the next trial, upon which another auditory “click” sounded to signify the beginning of a trial. The next trial automatically advanced if children did not touch the screen within a pre-specified amount of time (10,000 ms per stimulus to respond; i.e., 40,000 ms for set size 4). Two coders situated behind a one-way mirror independently coded verbal responses. Coders’ responses were checked for inter-rater agreement, and any discrepancies between coders were be resolved by checking video and audio recordings of the task.

Two practice blocks of five trials were administered prior to task administration for set sizes 3 and set size 4, 5, or 6. The practice block for set size 3 consisted of three stimuli, and the practice block for set size 4, 5, or 6 consisted of four stimuli. For set size 3, the letter always appeared second in each series. In set sizes 4 through 6, the letter was presented between the first and last stimuli, in a counterbalanced order (determined using a Latin Square design). To ensure that children understood the instructions, an 80% or higher success rate was required during practice blocks before beginning the experimental trials. Average stimuli correct per trial were computed for each set size (3, 4, 5, and 6) of each phonological working memory condition (auditory, visual, dual) and then averaged across set sizes to create three dependent variables (one for each phonological working memory condition).

Visuospatial working memory task. Visuospatial working memory was examined via a computerized task adapted from Rapport et al. (2008) that was programmed using SuperLab Pro 4.0 (Cedrus, San Pedro, CA). Colored dots (all black except for one red) sequentially appeared within boxes on an offset grid on a touch-screen computer, and children were instructed to touch the boxes in the same order that the black dots appeared, and to touch the box that the red dot appeared in last (see Figure 2). The offset grid consisted of three columns containing three boxes each (each measuring 2.85 x 2.85 cm). The grid was offset from a typical 3 x 3 grid to reduce the likelihood that children would utilize phonological encoding by assigning mental placeholders to each box (e.g., assigning values to each box like a telephone keypad). The red dot never appeared first or last in order to reduce the likelihood of recency or primacy effects. That is, for set size 3, the red dot always appeared second in the stimuli presentation, and in set sizes 4 through 6, the red dot was counterbalanced between the first and last stimuli.

The visuospatial task consisted of four blocks of varying set sizes (3, 4, 5, and 6) that correspond to the number of stimuli, and each block consisted of 24 trials. Blocks were presented in counter-balanced order (determined using a Latin Square design) to control for order effects. Each dot, measuring 2.22 cm in diameter, appeared sequentially for 800 ms with a 200 ms inter-stimulus interval. After each trial of stimuli presentation, a blank grid appeared to cue children to respond (see Figure 3). Children were allowed a maximum of 10,000 ms to respond to each stimulus (i.e., 10,000 ms for each dot). Following the children's entire response for a trial, or if the response time is exceeded, there is a 1,000 ms inter-trial interval. Afterward, the computer sounded an auditory "click" to indicate a new trial would be presented after an additional 1,000 ms.

Two practice blocks of five trials were administered prior to task administration for set size 3 and set size 4, 5, or 6. The practice block for set size 3 consisted of three stimuli, and the practice blocks for set size 4, 5, or 6 consisted of four stimuli. To ensure that children understood the instructions, an 80% or higher success rate was required during practice blocks before beginning the experimental trials. The dependent variable for this measure was the average stimuli correct per trial for each set size (3, 4, 5, and 6), averaged across set sizes.

Control condition. Children spent five minutes using the Microsoft Paint ® program to draw or paint anything of their choice at the beginning and end of each research session. This task served as a methodological control as it required children to engage the computer, but placed minimal working memory demands on children compared to the phonological tasks (Hudec et al., 2015). The use of two control conditions also allowed for the examination of potential fatigue effects on motor activity (i.e., a decrease in activity from the beginning of session to the end of session would suggest an effect of fatigue).

Motor activity. *MicroMini Motionlogger ® Actigraphs* were used to objectively measure motor activity. Three actigraphs were attached with a Velcro ® band to each participant's non-dominant wrist and above each ankle. Actigraphs were placed on participants' non-dominant hand so that measured motor activity was not confounded with task demands (e.g., touching the computer screen). Actigraphs were set to the proportional integrating measure, low (PIMlow) to measure the intensity of gross motor activity. The Observer XT version 8.0 (Noldus Information Technology, 2008) observation software was used to record time stamps for the start and stop of each task. Data from each of the actigraphs was uploaded into the Action4 (Ambulatory Monitoring Inc., 2010) computer program and matched to the recorded time stamps. Motor activity for each task was summed across the three sites (non-dominant hand, left ankle, and right ankle) to create a Total Extremity Score (TES) for each condition (phonological auditory, phonological visual, phonological dual, visuospatial, and control).

Procedure

After all rating scales were completed, children and parents participated in two clinical sessions to assess child intellectual functioning, academic achievement, developmental history, and any clinical symptomatology. The clinical sessions were scheduled for weekday mornings in order to obtain the best estimate of children's performance that was minimally affected by potential fatigue associated with testing later in the day. After obtaining informed consent and child assent in the first clinical session, a psychosocial interview was completed with the parent(s), while the WISC-V was administered to the child. Parents also completed a demographic information form with information on child ethnicity, parental education, and occupational status. In the second session, the clinical interview was administered to the parent(s), while the KTEA-3 was administered to the child.

Following the clinical testing sessions of the study, children participated in approximately three, three-hour research sessions scheduled for Saturday mornings or afternoons. The working memory tasks were completed as a part of a larger battery of experimental tasks and were administered in counterbalanced order across research sessions. Breaks were taken after every two to four tasks, or as needed, in order to reduce cognitive fatigue and possible frustration. After completion of the clinical and research sessions, parents attended a feedback session wherein the comprehensive psychoeducational report and discussion of findings were provided to parents.

Data Analytic Plan

All analyses were conducted using the Statistical Package for the Social Sciences (SPSS). Preliminary analyses examined potential between-group differences in sample characteristics via two-tailed independent samples *t*-tests (age, FSIQ, SES) and Pearson's chi-square test (ethnicity). Tiers I and II each utilized a mixed-model analysis of variance (ANOVA) to examine the potential interaction effects between group and condition of WM performance and motor activity, respectively. Significant interaction effects were probed using two-tailed independent samples *t*-tests to examine between-group effects at each condition and repeated-measures ANOVAs to examine within within-group effects. Main effects were interpreted for all non-significant interactions. In cases where Mauchly's Test of Sphericity indicated that the assumption of sphericity was violated, degrees of freedom were corrected using either the Huynh-Feldt or Greenhouse-Geisser corrections (Field, 2013).

CHAPTER III

RESULTS

A priori power analyses

Performance. A priori power analyses were conducted using G* Power software (v 3.0.10; Faul, Erdfelder, Lang, & Buchner, 2007) to determine the number of participants required to detect an interaction, between-group differences, and within-group differences in WM performance in a mixed-model ANOVA. An effect size of d = 0.87 was chosen based on the average magnitude of previously reported effect sizes for phonological and visuospatial storage/rehearsal processes (Alderson et al., 2010; Rapport et al., 2008). Based on an effect size of d = 0.87, power = .80 (as recommended by Cohen, 1992), α = .05, two groups, and four conditions (phonological auditory, phonological visual, phonological dual, and visuospatial), 28 total participants were needed to detect between-group differences, and 10 total participants were needed to detect within-group differences and interaction effects. The current study included 42 children (19 typically developing and 23 with ADHD), indicating that it was sufficiently powered.

Activity. A priori power analyses were conducted using G* Power software (v 3.0.10; Faul et al., 2007) to determine the number of participants required to detect an interaction, between-group differences, and within-group differences in motor activity in a repeated measures ANOVA. A Cohen's d effect size of 1.14 was chosen based on the average magnitude of effect sizes during tasks with high cognitive demands reported in a recent, comprehensive meta-analysis (Kofler et al., 2016). Based on an effect size of d = 1.14, power = .80 (as recommended by Cohen, 1992), $\alpha = .05$, two groups, and six conditions (phonological auditory, phonological visual, phonological dual, visuospatial, control 1, and control 2), 18 total participants were needed to detect between-group differences, and 6 total participants were needed to detect within-group differences and interaction effects. Consequently, the current study's inclusion of 42 children (19 typically developing and 23 with ADHD) suggests that it was sufficiently powered to reliably detect between group, within group, and interaction effects.

Outliers

Independent and dependent variables were independently screened by group (ADHD, TD) for univariate outliers as part of the preliminary analyses. Outliers were defined as values at least 3.29 standard deviations greater than or less than the mean for each group (i.e., $p < .001$; Tabachnick & Fidell, 2001). Values greater or less than 3.29 standard deviations from the mean were replaced with a value equal to ±3.29 standard deviations from the mean. Two outliers were identified for activity variables, and one outlier was identified for performance data.

Preliminary Analyses

Demographic data (age, SES, FSIQ, and ethnicity) was compared between groups using independent samples t-tests (age, FSIQ, SES) and Pearson's chi squared tests (ethnicity). Children in the ADHD group did not differ from children in the TD group with respect to age, $t(40) = 1.43$, $p = .16$, FSIQ[3], $t(39) = 1.83$, $p = .08$, gender, $t(40) = 0.76$, $p = .45$, or ethnicity, $\chi^2(4) = 2.92$, $p = .57$ and consequently, those variables were not included as covariates. Children with ADHD had lower socioeconomic status than children in the TD group, $t(40) = 2.57$, $p < .05$. SES was not included as a covariate in the analyses, however, given the high correlation between ADHD and SES (Rowland et al., 2018; Russell, Ford, Williams, & Russell, 2016) and the resulting potential for removing ADHD-related variability when covarying SES scores. Not surprisingly, children in the ADHD group had significantly higher *T* scores (all *p*s < .001) on the CBCL ADHD Problems DSM-oriented scale, $t(25.49) = 11.62$, the TRF ADHD Problems DSM-oriented scale, $t(27.19) = 9.63$, the C3-P DSM ADHD Inattention scale, $t(39) = 10.78$, the C3-P DSM ADHD Hyperactivity/ Impulsivity scale, $t(36.46) = 7.59$, the C3-T DSM ADHD Inattention scale, $t(39) = 11.40$, the C3-T DSM ADHD Hyperactivity/ Impulsivity scale, $t(29.86) = 8.56$, the CDI total scale, $t(40) = 3.71$, and the RCMAS-2 total scale, $t(38.48) = 4.06$. The results of the preliminary analyses are displayed in Table 1.

Tier I: Performance Across Working Memory Conditions

A 2 x 4 mixed model ANOVA examining the effect of group and working memory condition on performance yielded a significant main effect for group, $F(1, 40) = 14.86$, $p < .001$, such that the TD children exhibited greater WM performance than children with ADHD (Cohen's $d = 1.19$, 95% CI [0.54, 1.85]). Mauchly's test of sphericity indicated that the assumption of sphericity was violated, $\chi^2(5) = 11.71$, $p = .040$. Therefore, degrees of freedom were corrected using the Huynh-Feldt estimate of

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[3] One participant was administered the Woodcock-Johnson Test of Cognitive Abilities-IV (Schrank, McGrew, & Mather, 2014) rather than the WISC-V, as the WISC-V had been administered the previous year.

sphericity (ε = .92 for the main effect of condition). The main effect of condition was significant, $F(2.76, 110.52) = 23.26$, $p < .001$. Children's WM performance was significantly different across all tasks (*p*s < .01), with the exception of the visuospatial and phonological auditory task performance, which were not significantly different ($p = .17$). Performance during the phonological dual task was significantly greater than performance during the phonological visual task ($d = 0.61$), the phonological auditory task ($d = 0.98$), and the visuospatial task ($d = 1.11$). In addition, performance during the phonological visual task was significantly higher than during the phonological auditory ($d = 0.52$) and visuospatial ($d = 0.76$) tasks. The group by condition interaction was not significant, $F(2. 76, 110.52) = 1.92$, $p = .135$. WM performance results are displayed in Table 2.

Tier II: Motor Activity Across Conditions

A 2 x 6 mixed model ANOVA examined the effect of condition (phonological auditory, phonological visual, phonological dual, visuospatial, control 1, control 2) on activity level, with group serving as the between-subjects factor and condition serving as the within-subjects factor. Mauchly's test of sphericity indicated that the assumption of sphericity was violated for the main effect of condition, $\chi^2(14) = 41.54$, $p < .001$, so degrees of freedom were corrected using the Greenhouse-Geisser estimate of sphericity (ε = .67 for the main effect of condition). Results indicated a significant main effect of group, $F(1, 40) = 23.47$, $p < .001$ and condition, $F(3.35, 133.87) = 130.62$, $p < .001$. The interaction between group and condition was also significant, $F(3.35, 133.87) = 2.71$, $p = .042$ (see Figure 5 for a visual schematic of the group by condition interaction effect).

Two post hoc repeated-measures ANOVAs, one for each group, were used to examine differences in motor activity across conditions. Mauchly's test of sphericity indicated that the assumption of sphericity was violated for the main effect of condition for the TD group, $\chi^2(14) = 57.45$, $p < .001$; therefore, degrees of freedom were corrected using the Greenhouse-Geisser estimate of sphericity ($\varepsilon = .36$ for the main effect of condition). Effects of condition were significant for the for the TD group, $F(1.80, 32.47) = 46.82$, $p < .001$ and the ADHD group, $F(5, 110) = 91.42$, $p <.001$.

Post hoc pairwise comparisons indicated that motor activity of both groups was significantly greater during the experimental tasks (all ps < .001) relative to control conditions, and that motor activity was not significantly different between the control conditions (TD, $p = .920$; ADHD, $p = .398$). For both groups of children, motor activity was not significantly different across the three presentations (auditory, visual, and dual auditory-visual) of the phonological conditions (TD ps ranging from .111 to .665; ADHD ps ranging from .058 to .293). Motor activity exhibited by TD children during the visuospatial task, however, was significantly lower than activity exhibited during the phonological auditory ($p = .003$, $d = -0.80$), phonological visual ($p = .001$, $d = -0.93$), and phonological dual ($p = .001$, $d = -0.89$) tasks. Children with ADHD exhibited significantly lower activity during the visuospatial task compared to the phonological dual ($p = .023$, $d = -0.51$) task, but not relative to the phonological auditory ($p = .058$) or phonological visual ($p = .502$) tasks. Post hoc tests for both groups are displayed in Table 3.

Between-group differences at each condition were evaluated post hoc via t-tests. The ADHD group, compared to the TD group, displayed significantly more activity across all conditions (control 1 $t(36.63) = 3.84$, $p < .001$, $d = 1.17$, 95% CI [0.49, 1.80]; phonological auditory $t(40) = 3.94$, $p < .001$, $d = 1.22$, 95% CI [0.54, 1.86]; phonological visual $t(40) = 2.74$, $p = .009$, $d = 0.85$, 95% CI [0.20, 1.47]; phonological dual $t(40) = 4.35$, $p < .001$, $d = 1.35$, 95% CI [0.65, 1.99]; visuospatial $t(40) = 5.18$, $p < .001$, $d = 1.61$, 95% CI [0.88, 2.27]; control 2 $t(33.56) = 4.32$, $p < .001$, $d = 1.26$, 95% CI [0.58, 1.90]).

Post hoc Analysis of Motor Activity during Control Conditions

A post hoc analysis of motor activity during the control conditions was conducted to examine between-group differences in motor activity independent of WM variance. First, a composite WM score (average WM performance across all WM tasks) was regressed on activity during each of the control conditions (control 1, $R^2 = 0.18$; control 2, $R^2 = 0.17$). The resulting residual scores were used as dependent variables that reflect motor activity exhibited during the control conditions not related to WM demands (Rapport et al., 2009). A 2 x 2 mixed-model ANOVA with group as a between-subjects factor revealed a significant main effect of group, $F(1, 40) = 5.23$, $p = .028$. Surprisingly, TD children exhibited higher motor activity than children with ADHD after removing variance associated with WM performance. Neither the main effect of condition, $p = .99$, nor the group by condition interaction, $p = .90$, was significant.

CHAPTER IV

DISCUSSION

The present study experimentally manipulated presentation modality across three iterations of a phonological WM tasks to examine the role of episodic buffer demands on WM performance and objectively measured motor activity in children with ADHD and in typically developing children. Children with ADHD exhibited significantly worse phonological and visuospatial WM performance compared to their TD peers (d = 1.19), consistent with a substantial body of work indicating large-magnitude WM deficits in children with ADHD (Alderson et al., 2010; Friedman et al., 2017; Kasper et al., 2012; Rapport et al., 2008). Moreover, both groups exhibited the lowest WM performance during the visuospatial task. This finding is consistent with previous experimental (Barnett, Maruff, & Vance, 2005; Rapport et al., 2008; van Ewijk et al., 2014) and meta-analytic findings (Kasper et al., 2012; Martinussen et al., 2005) of large-magnitude visuospatial storage/rehearsal and WM deficits in children with ADHD, and worse visuospatial relative to phonological WM performance in TD children (Rapport et al., 2008).

Overall, children recalled more phonological stimuli when the stimuli were presented visually relative to auditorily, and recalled the most stimuli when they were simultaneously presented visually and auditorily (i.e., during dual, multimodal presentation). There are a number of possible explanations for this finding. Consistent with our a priori hypotheses, these findings appear to provide evidence of variance in demands associated with multimodal binding via the episodic buffer. That is, when children hear phonological stimuli (e.g., the phonological auditory task), WM automatically grants phonological stimuli access to the phonological buffer/loop (Baddeley, 2007, 2012), creating a verbal code. In contrast, when children are presented phonological stimuli as visual text (e.g., the phonological visual task), stimuli are visually encoded, converted to phonological information via orthographic to phonological recoding processes, and finally granted access to the phonological buffer/loop (i.e., a verbal code; Baddeley, 2007) and/or the episodic buffer as bound multimodal information. Thus, the use of multimodal (i.e., both verbal and visual) code may have facilitated children's improved performance during the phonological visual condition, and the phonological dual condition. This explanation is consistent with findings that the episodic buffer frees executive resources for further manipulation of sensory input by providing storage of and access to bound information, (e.g., correct reordering of stimuli; Baddeley, 2012; Baddeley, Allen, & Hitch, 2010). An alternative explanation that warrants consideration is that performance during the phonological auditory condition was disrupted by articulatory suppression effects, such that hearing stimuli presented by the computer interfered with the children's subvocal rehearsal (Fatzer & Robers, 2012). This interpretation is unlikely, however, as children's WM performance during both auditory and dual presentations would be expected to fall below performance during the visual presentation, given auditory presentation of stimuli by the computer occurred during both the phonological auditory and phonological dual conditions. This explanation is also inconsistent with findings from basic cognitive research that suggests episodic buffer processes attenuate the effect of articulatory suppression during digit span tasks (Baddeley, 2007; Larsen & Baddeley, 2003).

Unexpectedly, the interaction between group and stimulus presentation modality on WM performance was not significant. Although two previous investigations of the episodic buffer in ADHD (Alderson, et al., 2015; Kofler et al., 2018) found significant interactions, closer inspection of the direction of the effects indicates equivocal findings, as Alderson et al. (2015) concluded that children with ADHD did not benefit from the episodic buffer to the same extent as their TD peers, while Kofler et al. (2018) suggested that the episodic buffer is intact in children with ADHD. There are several possible reasons for the mixed findings from the current and previous studies. One possibility is Kofler and colleagues' (2018) use of a keyboard to capture responses during the visuospatial and episodic buffer tasks. That is, children had to visually encode information presented on a computer screen, shift attention from the computer screen to a keyboard, map 2-dimensional cognitive representations of the stimuli unto a 3-dimensional keyboard, and finally, output the information by key presses. Notably, these demands were not included in Kofler et al.'s phonological tasks. In contrast, the phonological visual and phonological dual tasks used by Alderson et al. (2015) and the current study assessed children's recall across all phonological tasks via children's direct-verbal output. Consequently, in contrast to Alderson et al. and the current study, it is possible that Kofler and colleague's findings reflect variance in central executive -related attentional demands across tasks, rather than episodic buffer processes (Alderson et al., 2015; Baddeley, 2007).

Another potential explanation for the discrepant findings across studies is variation in sample characteristics. Specifically, the sample utilized by Alderson et al. (2015) was more homogenous than the current study's sample, as it was smaller, exclusively male, and included fewer children with comorbid disorders. Likewise, the control group examined by Kofler et al. (2018) was markedly different from the TD control group examined in the current study. Specifically, Kofler and colleagues examined a mixed sample of TD children and children diagnosed with anxiety, depression, ODD, and autism spectrum disorder. This procedure likely obscured potential inferences about the relationship between episodic buffer demands and motor activity in the greater population of children with ADHD, as the population to which findings might be generalized is unclear, and a replication study that used identical methodology would likely produce different results.

The novel contribution of the current study was its examination of the effect of varying episodic buffer demands (via manipulation of phonological stimulus presentation modality) on ADHD-related hyperactivity. Compared to TD children, children with ADHD exhibited a disproportionate increase in motor activity from control to phonological and visuospatial WM conditions, consistent with Rapport et al.'s (2009) prediction of a causal relationship between WM demands and increased motor activity. Interestingly, motor activity remained relatively stable across phonological conditions, but was lower during the visuospatial condition, contrasting our a priori prediction that variance in episodic buffer demands would be functionally related to changes in motor activity across groups. One potential explanation for the null within-group effect across phonological conditions is that the relationship between ADHD-related hyperactivity and working memory is predominantly attributable to central executive processes, rather than phonological, visuospatial, or episodic buffer storage/rehearsal components. The phonological WM tasks were designed to vary only by presentation modality and to place equivalent demands on the central executive so that any observed performance differences could be confidently attributed to presentation modality (i.e., encoding of information and episodic buffer storage). Accordingly, elevated but stable motor activity exhibited during the phonological conditions, relative to the control conditions, must be due to central executive demands that were held constant across the phonological conditions.

The TD group's significantly lower motor activity during the visuospatial task relative to all phonological conditions, and the ADHD group's lower activity during the visuospatial task relative to the phonological dual task, is notable and warrants consideration. These findings contrast evidence from basic cognitive literature that suggests greater central executive involvement in visuospatial, compared to verbal, short-term memory (Baddeley, Cocchini, Della Sala, Logie, & Spinller, 1999; Miyake, Friedman, Rettinger, Shah, & Hegarty, 2001), as well as empirical (Alderson et al., 2012, 2015; Friedman et al., 2017; Rapport et al., 2008) and meta-analytic (Kasper et al., 2012) findings that consistently suggest the central executive is the most impaired WM component and most strongly related to motor activity in children with the disorder. Alternatively, the relative decrease in motor activity during the visuospatial condition may simply be due to task demands that require children to orient physically toward the computer screen to correctly encode stimuli and execute responses. In contrast, momentary lapses of attention during the phonological auditory and phonological dual conditions due to internal or external singleton distractors (Yantis & Jonides, 1984) or extraneous prepotent stimuli (Diamond, 2013) do not preclude successful encoding of auditorily delivered stimuli. Moreover, all phonological conditions required verbal responses that could be given during moments of considerable motor activity (e.g., spinning in the chair), while visuospatial responses required relatively stationary orientation toward the computer screen.

Finally, our finding that children with ADHD displayed greater motor activity than TD children during the control conditions was unexpected, as the functional working memory model (Rapport et al., 2001) predicts that activity during conditions with low WM demands would not differ between children with ADHD and TD children. Although the control conditions were designed to minimize demands placed on WM, in hindsight, even relatively simple tasks (e.g., drawing on a computer screen) elicit some WM demands, as consciousness involves focused attention and information processing (Baddeley, 2007). To further probe this unexpected finding, a post hoc examination was conducted to examine between-group differences in motor activity independent of WM variance. After statistically removing WM variance associated with motor activity during the control conditions, the activity of TD children was surprisingly above that of children with ADHD. There are a number of possible explanations for this unexpected finding. One possibility is that the current finding is spurious, as previous studies that employed this statistical approach (Lea, Alderson, Patros, Tarle, Arrington, & Grant, 2017; Rapport et al., 2009) did not find between-group effects after removing variance associated with WM. Alternatively, our discrepant finding may reflect subtle procedural differences with respect to the method by which WM variance was removed from the control conditions.

Specifically, Rapport et al. (2009) statistically removed variance associated with a central executive variable that reflected shared variance between phonological visual and visuospatial tasks, while Lea et al. (2017) followed a similar procedure but removed variance associated with a central executive variable (shared variance between a phonological auditory and visuospatial task), a phonological storage/rehearsal variable, and a visuospatial storage/rehearsal variable. In contrast, we removed variance associated with an aggregated phonological auditory, phonological visual, phonological dual, and visuospatial performance score that theoretically captured all components of working memory. To that end, our unexpected finding of greater motor activity in the TD group after removing WM variance underscores the strength of the relationship between WM demands and motor activity exhibited by children with ADHD. Moreover, these findings may suggest that the link between motor activity and working memory is stronger in children with ADHD compared to TD peers, which may partially contribute to consistent findings that motor activity exhibited by affected children disproportionately increases during high WM demand conditions (Alderson et al., 2012; Hudec et al., 2015; Rapport et al., 2009). Finally, it is plausible that processes other than WM contribute to variance in motor activity (e.g., self-control, Patros et al., 2017; interference control, Hartanto et al., 2016), and future research on the subject is warranted.

Despite the methodological refinements of the current study (comprehensive grouping procedure, experimental manipulation of WM demands, objective measures of activity), several potential limitations warrant consideration. The ADHD group included only children with the combined presentation to maximize hyperactivity symptoms in the ADHD sample, as the major focus of this paper was to examine the episodic buffer in relation to motor activity in children with ADHD. Although the exclusion of the inattentive presentation may restrict generalizability to all presentations of ADHD, greater power to detect effects was expected with a sample of children with the combined presentation of ADHD, relative to a well-defined sample of TD children. Another potential limitation of the current study is the low percentage of girls in the sample, which reduces generalizability of findings to the larger population of children with ADHD. Future studies with a larger proportion of girls will be needed to assess the external validity of our findings. Lastly, the current study had a relatively low sample size of 23 children with ADHD and 19 TD children. A priori power analyses, however, suggest the current study was sufficiently powered to detect potential main effects and interactions for both performance and activity data. Nonetheless, future studies with larger sample sizes will likely be needed to further strengthen confidence in the generalizability of these findings and overall, replications of the current findings with different ages, race/ethnicity compositions, and ADHD presentations will be fruitful. Taken together, findings from this study indicate that children benefit from dual (visual and verbal) modality presentation of information, relative to single visual or auditory modality presentation, and align with previous research (Penney et al., 1989). For example, studies of comprehension and retention of educational information indicate that media with closed captions (i.e., multimodal auditory and visual input) may lead to improved understanding and retention of both educational and entertainment materials (Mousavi, Low, & Sweller, 1975). Although motor activity remained relatively stable across the phonological conditions in the current study, Kofler et al.'s (2018) conclusion of intact episodic buffer functioning in children with ADHD may be premature. Rather than being unimpaired, it may be more accurate that episodic buffer functioning is *less* impaired relative to the exceptionally large and well-documented phonological storage/rehearsal, visuospatial storage/rehearsal, and central executive deficits in children with ADHD (Alderson et al., 2015; Kasper et al., 2012; Rapport et al., 2009). Nevertheless, further research on different types and measurement of the episodic buffer may be needed. For example, recent evidence suggests there may be more than one episodic buffer (e.g., for taste, smell; Baddeley & Hitch, 2018) and a preponderance of previous research indicates that there is considerable variation in what information may be bound (Baddeley, Allen, & Vargha-Khadem, 2010), such as perceptual features (e.g., shape and color; Allen, Baddeley, & Hitch, 2006; Baddeley, Allen, & Hitch, 2011; Karlsen, Allen, Baddeley, & Hitch, 2010), visual-spatial stimuli (e.g., shapes to spatial locations; Farrell & Oberauer, 2014; Gray et al., 2017), sentential information (Baddeley, Hitch, & Allen, 2009), and verbal information across modalities (e.g. spoken text and sign language, Rudner, Fransson, Ingvar, Nyberg, & Rönnberg, 2007; auditory nonwords and abstract shapes, Wang, Allen, Lee, & Hsieh, 2015). Additional research on the episodic buffer (e.g., studies examining binding of features or semantic information to long-term memory) in children with ADHD is expected to prove fruitful in the understanding of the ADHD endophenotype.

REFERENCES

Achenbach, T. M., & Rescorla, L. A. (2001). *Manual for the ASEBA school-age forms and profiles*. Burlington, VT: University of Vermont, Research Center for Children, Youth, and Families.

Alderson, R. M., Kasper, L. J., Patros, C. H. G., Hudec, K. L., Tarle, S. J., & Lea, S. E. (2015). Working memory deficits in boys with attention deficit/hyperactivity disorder (ADHD): An examination of orthographic coding and episodic buffer processes. *Child Neuropsychology, 21*(4), 509-530. doi:10.1080/09297049.2014.917618

Alderson, R. M., Patros, C. H. G., Tarle, S. J., Hudec, K. L., Kasper, L. J., & Lea, S. E. (2015). Working memory and behavioral inhibition in boys with ADHD: An experimental examination of competing models. *Child Neuropsychology*, 1-18. doi:10.1080/09297049.2015.1105207

Alderson, R. M., Rapport, M. D., Hudec, K. L., Sarver, D. E., & Kofler, M. J. (2010). Competing core processes in attention-deficit/hyperactivity disorder (ADHD): Do working memory deficiencies underlie behavioral inhibition deficits? *Journal of Abnormal Child Psychology, 38*(4), 497-507. doi:10.1007/s10802-010-9387-0

Alderson, R. M., Rapport, M. D., Kasper, L. J., Sarver, D. E., & Kofler, M. J. (2012). Hyperactivity in boys with attention deficit/hyperactivity disorder (ADHD): The association between deficient behavioral inhibition, attentional processes, and objectively measured activity. *Child Neuropsychology, 18*(5), 487-505. doi:10.1080/09297049.2011.631905

Allen, R. J., Baddeley, A. D., & Hitch, G. J. (2006). Is the binding of visual features in working memory resource-demanding?. *Journal of Experimental Psychology: General*, *135*(2), 298.

Ambulatory Monitoring Incorporated. (2010). *The micromini motionlogger actigraph and family of single sensor recorders* [User's manual to accompany Act Millenium version 3.31.0.0 and higher (Revision 3.1)]: Ardsley, NY: Author.

American Psychiatric Association. (2013). *Diagnostic and statistical manual of mental disorders* (5th ed.). Washington, DC: Author.

Babinski, L. M., Hartsough, C. S., & Lambert, N. M. (1999). Childhood conduct problems, hyperactivity-impulsivity, and inattention as predictors of adult criminal activity. *Journal of Child Psychology and Psychiatry, 40*(3), 347-355. doi:10.1111/1469-7610.00452

Baddeley, A. (2003). Working memory: Looking back and looking forward. *Nature Reviews Neuroscience*, *4*, 829–839.

Baddeley, A. (2007). *Working memory, thought, and action*: Oxford University Press, New York, NY.

Baddeley, A. (2012). Working memory: Theories, models, and controversies. *Annual Review of Psychology, 63*(1), 1-29. doi:10.1146/annurev-psych-120710-100422

Baddeley, A., Allen, R. J., & Hitch, G. J. (2010). Investigating the episodic buffer. *Psychologica Belgica, 50*(3-4), 223-243. doi:10.5334/pb-50-3-4-223

Baddeley, A. D., Allen, R. J., & Hitch, G. J. (2011). Binding in visual working memory: The role of the episodic buffer. *Neuropsychologia*, *49*(6), 1393-1400.

Baddeley, A., Cocchini, G., Della Sala, S., Logie, R. H., & Spinnler, H. (1999). Working memory and vigilance: Evidence from normal aging and Alzheimer's disease. Brain and cognition, 41(1), 87-108.

Baddeley, A. D., & Hitch, G. (1974). Working memory. In *Psychology of learning and motivation* (Vol. 8, pp. 47-89). Academic press.

Baddeley, A. D., & Hitch, G. (2018). The phonological loop as a buffer store: An update. *Cortex* epub ahead of pritn

Baddeley, A. D., Hitch, G. J., & Allen, R. J. (2009). Working memory and binding in sentence recall. *Journal of Memory and Language, 61*(3), 438-456. doi:10.1016/j.jml.2009.05.004

Barkley, R. A. (1997). Behavioral inhibition, sustained attention, and executive functions: Constructing a unifying theory of ADHD. *Psychological Bulletin, 121*(1), 65-94. doi:10.1037/0033-2909.121.1.65

Barkley, R. A. (2014). *Attention-deficit hyperactivity disorder: A handbook for diagnosis and treatment.*. New York, NY, US: Guilford Press.

Barnett, R., Maruff, P., & Vance, A. (2005). An investigation of visuospatial memory impairment in children with attention deficit hyperactivity disorder (ADHD), combined type. *Psychological medicine*, 35(10), 1433-1443.

Basso, A. H., Spinnler, G.,Vallar, G. and Zanobia, E. (1982). Left hemisphere damage and selective impairment of auditory verbal short-term memory: a case study. *Neuropsychologica*, 20, 274.

Biederman, J., Wozniak, J., Kiely, K., Ablon, S., Faraone, S., Mick, E., . . . Kraus, I. (1995). CBCL clinical scales discriminate prepubertal children with structured interview-derived diagnosis of mania from those with ADHD. *Journal of the American Academy of Child & Adolescent Psychiatry, 34*(4), 464-471. doi:10.1097/00004583-199504000-00013

Birmaher, B., Ehmann, M., Axelson, D. A., Goldstein, B. I., Monk, K., Kalas, C., . . . Brent, D. A. (2009). Schedule for affective disorders and schizophrenia for school-age children (K-SADS-PL) for the assessment of preschool children – A preliminary psychometric study. *Journal of Psychiatric Research, 43*(7), 680-686. doi:10.1016/j.jpsychires.2008.10.003

Cohen, J. (1992). A power primer. *Psychological Bulletin, 112*(1), 155-159. doi:10.1037/0033-2909.112.1.155

Conners, C. K. (2008). *Conners 3rd Edition (Conners 3)*. Los Angeles, CA: Multi-Health Systems, Inc (MHS).

Diamond, A. (2013). Executive functions. *Annual review of Psychology*, *64*, 135-168.

Fassbender, C., & Schweitzer, J. B. (2006). Is there evidence for neural compensation in attention deficit hyperactivity disorder? A review of the functional neuroimaging literature. *Clinical Psychology Review, 26*(4), 445-465. doi:10.1016/j.cpr.2006.01.003

Fatzer, S., & Roebers, C. (2012). Language and executive functions: The effect of articulatory suppression on executive functioning in children. *Journal of Cognition and Development*, 13(4), 454–472. doi:10.1080/15248372.2011.608322

Farrell, S., & Oberauer, K. (2014). Working memory for cross-domain sequences. *The Quarterly Journal of Experimental Psychology*, *67*(1), 33-44.

Faul, F., Erdfelder, E., Lang, A. G., & Buchner, A. (2007). G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods, 39*, 175-191.

Fergusson, D. M., Lynskey, M. T., & Horwood, L. J. (1997). Attentional difficulties in middle childhood and psychosocial outcomes in young adulthood. *Child Psychology & Psychiatry & Allied Disciplines, 38*(6), 633-644. doi:10.1111/j.1469-7610.1997.tb01690.x

Field, A. (2013). *Discovering statistics using IBM SPSS statistics*. Sage.

Friedman, L. M., Rapport, M. D., Orban, S. A., Eckrich, S. J., & Calub, C. A. (2017). Applied problem solving in children with ADHD: The mediating roles of working memory and mathematical calculation. *Journal of Abnormal Child Psychology*. doi:10.1007/s10802-017-0312-7

Gaub, M., & Carlson, C. L. (1997). Gender differences in ADHD: A meta-analysis and critical review. *Journal of the American Academy of Child & Adolescent Psychiatry, 36*(8), 1036-1045. doi:10.1097/00004583-199708000-00011

Gualtieri, C. T., & Johnson, L. G. (2005). ADHD: Is Objective Diagnosis Possible? *Psychiatry (Edgmont), 2*(11), 44-53.

Gray, S., Green, S., Alt, M., Hogan, T., Kuo, T., Brinkley, S., & Cowan, N. (2017). The structure of working memory in young children and its relation to intelligence. *Journal of Memory and Language*, *92*, 183-201.

Halperin, J. M., & Schulz, K. P. (2006). Revisiting the role of the prefrontal cortex in the pathophysiology of attention-deficit/hyperactivity disorder. *Psychological Bulletin, 132*(4), 560-581. doi:10.1037/0033-2909.132.4.560

Hartanto, T. A., Krafft, C. E., Iosif, A. M., & Schweitzer, J. B. (2016). A trial-by-trial analysis reveals more intense physical activity is associated with better cognitive control performance in attention-deficit/hyperactivity disorder. *Child Neuropsychology, 22*(5), 618-626. doi:10.1080/09297049.2015.1044511

Hudec, K. L., Alderson, R. M., Patros, C. H. G., Lea, S. E., Tarle, S. J., & Kasper, L. J. (2015). Hyperactivity in boys with attention-deficit/hyperactivity disorder (ADHD): The role of executive and non-executive functions. *Research in Developmental Disabilities, 45-46*, 103-109. doi:10.1016/j.ridd.2015.07.012

Humphreys, K. L., Galán, C. A., Tottenham, N., & Lee, S. S. (2016). Impaired social decision-making mediates the association between ADHD and social problems. *Journal of abnormal child psychology*, *44*(5), 1023-1032.

Karlsen, P. J., Allen, R. J., Baddeley, A. D., & Hitch, G. J. (2010). Binding across space and time in visual working memory. *Memory & Cognition, 38*(3), 292-303. doi:10.3758/MC.38.3.292

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*(7), 605-617. doi:10.1016/j.cpr.2012.07.001

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*(7), 980-988. doi: 10.1097/00004583-199707000-00021

Kaufman, A. S., & Kaufman, N. L. (2004). Kaufman Assessment Battery for Children (2nd ed.). Circle Pines,MN: American Guidance Service.

Kaufman, A. S., & Kaufman, N. L. (2014). *Kaufman test of educational achievement, third edition*. Bloomington, MN: NCS: Pearson.

Kaufman, A. S., Kaufman, N. L., & (with Breaux, N. C.) (2014). Technical and Interpretive Manual *Kaufman test of educational achievement, third edition*. Bloomington, MN: NCS Pearson.

Kofler, M. J., Raiker, J. S., Sarver, D. E., Wells, E. L., & Soto, E. F. (2016). Is hyperactivity ubiquitous in ADHD or dependent on environmental demands? Evidence from meta-analysis. *Clinical Psychology Review, 46*, 12-24. doi:10.1016/j.cpr.2016.04.004

Kofler, M. J., Spiegel, J. A., Austin, K. E., Irwin, L. N., Soto, E. F., & Sarver, D. E. (2018). Are Episodic Buffer Processes Intact in ADHD? Experimental Evidence and Linkage with Hyperactive Behavior. *Journal of Abnormal Child Psychology*, *46*(6), 1171-1185.

Kovacs, M. (2003). *Children's Depression Inventory (CDI): Technical Manual Update*. North Tonawanda, NY: Multi-Health Systems, Inc.

Lambek, R., Tannock, R., Dalsgaard, S., Trillingsgaard, A., Damm, D., & Thomsen, P. H. (2011). Executive dysfunction in school-age children with ADHD. *Journal of Attention Disorders*, *15*(8), 646-655. doi: 10.1177/1087054710370935

Larsen, J. D., & Baddeley, A. (2003). Disruption of verbal STM by irrelevant speech, articulatory suppression, and manual tapping: Do they have a common source?. *The Quarterly Journal of Experimental Psychology Section A*, *56*(8), 1249-1268.

Lea, S. E., Alderson, R. M., Patros, C. H., Tarle, S. J., Arrington, E. F., & Grant, D. M. (2018). Working Memory and Motor Activity: A Comparison Across Attention-Deficit/Hyperactivity Disorder, Generalized Anxiety Disorder, and Healthy Control Groups. *Behavior Therapy*, 49(3), 419-434.

Martinussen, R., Hayden, J., Hogg-Johnson, S., & Tannock, R. A meta-analysis of working memory impairments in children with attention-deficit/hyperactivity disorder. *Journal of the American Academy of Child & Adolescent Psychiatry, 44*(4), 377-384. doi:10.1097/01.chi.0000153228.72591.73

Miyake, A., Friedman, N. P., Rettinger, D. A., Shah, P., & Hegarty, M. (2001). How are visuospatial working memory, executive functioning, and spatial abilities related? A latent-variable analysis. *Journal of experimental psychology: General*, *130*(4), 621.

Mousavi, S. Y., Low, R., & Sweller, J. (1995). Reducing cognitive load by mixing auditory and visual presentation modes. *Journal of Educational Psychology, 87*(2), 319-334.

Moreno, R., & Mayer, R. E. (2002). Verbal redundancy in multimedia learning: When reading helps listening. *Journal of Educational Psychology, 94*(1), 156-163.doi:/10.1037/0022-0663.94.1.156

Noldus Information Technology. (2008). *The Observer XT reference manual 8.0*. Wageningen, Netherlands: Author.

Ostrander, R., Weinfurt, K. P., Yarnold, P. R., & August, G. J. (1998). Diagnosing attention deficit disorders with the Behavioral Assessment System for Children and the Child Behavior Checklist: Test and construct validity analyses using optimal discriminant classification trees. *Journal of Consulting and Clinical Psychology, 66*(4), 660-672. doi:10.1037/0022-006X.66.4.660

Patros, C. H. G., Alderson, R. M., Hudec, K. L., Tarle, S. J., & Lea, S. E. (2017). Hyperactivity in boys with attention-deficit/hyperactivity disorder: The influence of underlying visuospatial working memory and self-control processes. *Journal of Experimental Child Psychology, 154*, 1-12. doi:10.1016/j.jecp.2016.09.008

Pelham, J. W. E., Fabiano, G. A., & Massetti, G. M. (2005). Evidence-Based Assessment of Attention Deficit Hyperactivity Disorder in Children and Adolescents. *Journal of Clinical Child & Adolescent Psychology, 34*(3), 449-476. doi:10.1207/s15374424jccp3403_5

Penney, C. (1989). Modality effects and the structure of short-term verbal memory. Memory & Cognition, 17, 398-422.

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*(6), 825-837. doi:10.1007/s10802-008-9215-y

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*(4), 521-534. doi:10.1007/s10802-008-9287-8

Rapport, M. D., Chung, K.-M., Shore, G., & Isaacs, P. (2001). A conceptual model of child psychopathology: Implications for understanding attention deficit hyperactivity disorder and treatment efficacy. *Journal of Clinical Child Psychology, 30*(1), 48-58. doi:10.1207/S15374424JCCP3001_6

Reynolds, C. R., & Richmond, B. O. (2008). *Revised Children's Manifest Anxiety Scale-2 (RCMAS-2) Second Edition Manual*. Los Angeles, CA: Western Psychological Services.

Rowland, A. S., Skipper, B. J., Rabiner, D. L., Qeadan, F., Campbell, R. A., Naftel, A. J., & Umbach, D. M. (2018). Attention□deficit/hyperactivity Disorder (ADHD): Interaction between socioeconomic status and parental history of ADHD determines prevalence. *Journal of Child Psychology and Psychiatry*, *59*(3), 213-222.

Rudner, M., Fransson, P., Ingvar, M., Nyberg, L., & Rönnberg, J. (2007). Neural representation of binding lexical signs and words in the episodic buffer of working memory. *Neuropsychologia, 45*(10), 2258-2276. doi:10.1016j.neuropsychologia.2007.02.017

Russell, A. E., Ford, T., Williams, R., & Russell, G. (2016). The association between socioeconomic disadvantage and attention deficit/hyperactivity disorder (ADHD): a systematic review. *Child Psychiatry & Human Development*, *47*(3), 440-458.

Sarver, D. E., Rapport, M. D., Kofler, M. J., Raiker, J. S., & Friedman, L. M. (2015). Hyperactivity in attention-deficit/hyperactivity disorder (ADHD): Impairing deficit or compensatory behavior?. *Journal of abnormal child psychology*, *43*(7), 1219-1232.

Schrank, F. A., McGrew, K. S., & Mather, N. (2014). *Woodcock-Johnson IV Tests of Cognitive Abilities.* Rolling Meadows, IL: Riverside.

Shallice, T., & Warrington, E. K. (1970). Independent functioning of verbal memory stores:
A neuropsychological study. *Quarterly Journal of Experimental Psychology*, 22, 261–73.

Smith, E. E., Jonides, J., & Koeppe, R. A. (1996). Dissociating verbal and spatial working memory using PET. *Cerebral Cortex, 6*(1), 11-20. doi:10.1093/cercor/6.1.11

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*(4), 345-355. doi:.1097/00004583-201004000-00009

SuperLab 4.0 [Computer program]. San Pedro, CA: Cedrus Corporation.

Tabachnick, B. G., & Fidell, L. S. (2001). *Using multivariate statistics (5th ed.)*. New York, NY: Pearson Inc.

Tarle, S. J., Alderson, R. M., Patros, C. H. G., Lea, S. E., Hudec, K. L., & Arrington, E. F. (2017). Attention-deficit/hyperactivity disorder and phonological working memory: Methodological variability affects clinical and experimental performance metrics. *Neuropsychology, 31*(4), 383-394. doi:10.1037/neu0000364 van Ewijk, H., Heslenfeld, D. J., Luman, M., Rommelse, N. N., Hartman, C. A., Hoekstra, P., ... & Oosterlaan, J. (2014). Visuospatial working memory in ADHD patients, unaffected siblings, and healthy controls. *Journal of attention disorders*, *18*(4), 369-378.

Wang, S., Allen, R. J., Lee, J. R., & Hsieh, C.-E. (2015). Evaluating the developmental trajectory of the episodic buffer component of working memory and its relation to word recognition in children. *Journal of Experimental Child Psychology, 133*, 16-28. doi:10.1016/j.jecp.2015.01.002

Wechsler, D. (2003). *Wechsler Intelligence Scale for Children* (4th ed.). San Antonio, TX: NCS Pearson.

Wechsler, D. (2014). *Wechsler Intelligence Scale for Children* (5th ed.). San Antonio, TX: NCS Pearson.

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*(11), 1336-1346. doi: 10.1016/j.biopsych.2005.02.006

Yantis, S., & Jonides, J. (1984). Abrupt visual onsets and selective attention: evidence from visual search. *Journal of Experimental Psychology: Human perception and performance*, *10*(5), 601.

TABLES AND FIGURES

Table 1. Sample characteristics

	TD (n = 19) *M (SD)*	ADHD (n = 23) *M (SD)*	t	χ^2
<u>Sample Characteristics</u>				
Age in years	10.21 (1.45)	9.55 (1.51)	1.43	
FSIQ	108.39 (15.07)	101.30 (9.61)	1.83	
Gender			0.76	
Ethnicity				2.92
Caucasian	15	18		
Native American	0	2		
Asian	1	0		
Hispanic	1	1		
Biracial	2	2		
SES[a]	53.00 (10.85)	44.61 (10.27)	2.57*	
CBCL DSM-ADHD *T*	51.05 (1.87)	69.30 (7.25)	-11.62***	
TRF DSM-ADHD *T* score	51.05 (2.17)	65.61 (6.85)	-9.63***	
C3-P ADHD-I *T* score	47.16 (8.29)	76.77 (9.16)	-10.78***	
C3-P ADHD-HI *T* score	48.26 (8.66)	74.50 (13.28)	-7.59***	
C3-T ADHD-I *T* score	45.53 (5.79)	71.73 (8.44)	-11.40***	
C3-T ADHD-HI *T* score	45.63 (6.08)	73.36 (13.69)	-8.58***	
CDI Total *T* score	41.53 (6.84)	50.91 (9.10)	-3.71***	
RCMAS-2 Total *T* score	37.32 (7.27)	48.74 (10.88)	-4.06***	

Note. TD = typically developing; ADHD = attention-deficit/hyperactivity disorder; FSIQ = Full Scale Intelligence Quotient; SES = socioeconomic status; CBCL = Child Behavior Checklist; DSM-ADHD = Attention-Deficit/Hyperactivity Problems Scale; TRF = Teacher Report Form; C3-P = Conners-3 Parent Rating Scale; ADHD-I = DSM ADHD Inattention Subscale; ADHD-HI = DSM ADHD Hyperactive/Impulsive Subscale; C3-T = Conners-3 Teacher Rating Scale.
[a] Scores are based on the Four Factor Index of Social Status (Hollingshead, 1975).
* $p < .05$, ** $p < .01$, *** $p < .001$

Table 2. Composite working memory scores across experimental tasks

	TD (n = 19) *M (SD)*	ADHD (n = 23) *M (SD)*	*F*	Pairwise Comparisons
Phonological Auditory (PHA)	3.52 (.72)	2.55 (.74)		
Phonological Visual (PHV)	3.57 (.67)	2.89 (.75)		
Phonological Dual (PHD)	3.80 (.56)	3.04 (.78)		
Visuospatial (VS)	3.35 (.67)	2.49 (.87)		
Between Group			14.86***	
Within Group			23.26***	VS = PHA; VS < PHV < PHD; PHA < PHV < PHD
Group x Task			1.92	

Note. TD = typically developing; ADHD = attention-deficit/hyperactivity disorder; ***$p < .001$

Table 3. Composite activity scores across experimental conditions

	TD (n = 19) *M* *(SD)*	ADHD (n = 23) *M* *(SD)*	*F*	*t*	*d*	Post hoc
Control 1 (C1)	10905.39 (5187.46)	19254.99 (8734.73)		3.84***	1.17	
Phonological Auditory (PHA)	32009.30 (13049.97	46224.77 (10350.86)		3.94***	1.22	
Phonological Visual (PHV)	33828.54 (14571.24	44474.38 (10583.95)		2.74**	0.85	
Phonological Dual (PHD)	33130.73 (11619.45	48340.44 (10989.03)		4.35***	1.35	
Visuospatial (VS)	25804.59 (10133.15	42965.43 (11119.71)		5.18***	1.61	
Control (C2)	11017.37 (4810.98)	20907.55 (9626.80)		4.32***	1.26	
Between Group			23.47***			
Within Group			130.62***			
Group x Condition			2.71*			
TD Post hoc Repeated Measures ANOVA			46.82***			C1, C2 < VS< PHA= PHV= PHD
ADHD Post hoc Repeated Measures ANOVA			91.42***			C1, C2 < VS, PHA= PHV= PHD; VS < PHD; VS= PHA= PHV

Note. TD = typically developing; ADHD = attention-deficit/hyperactivity disorder
* $p < .05$, ** $p < .01$, *** $p < .001$

Figure 1. Phonological working memory task.

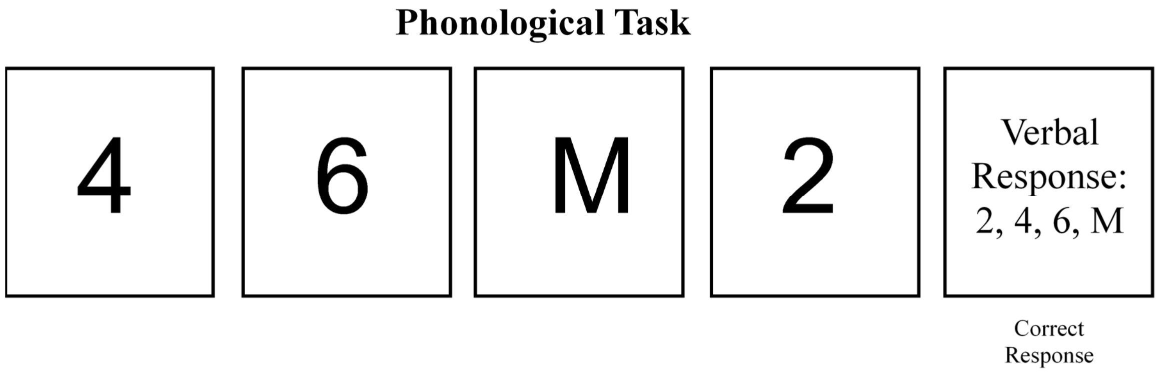


Figure 2. Visuospatial working memory task

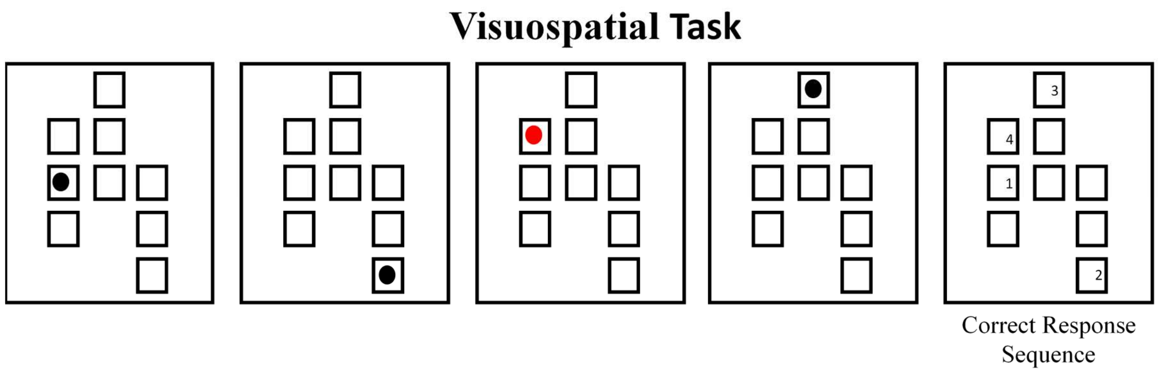


Figure 3. Blank response grid presented to participants in visuospatial trials.

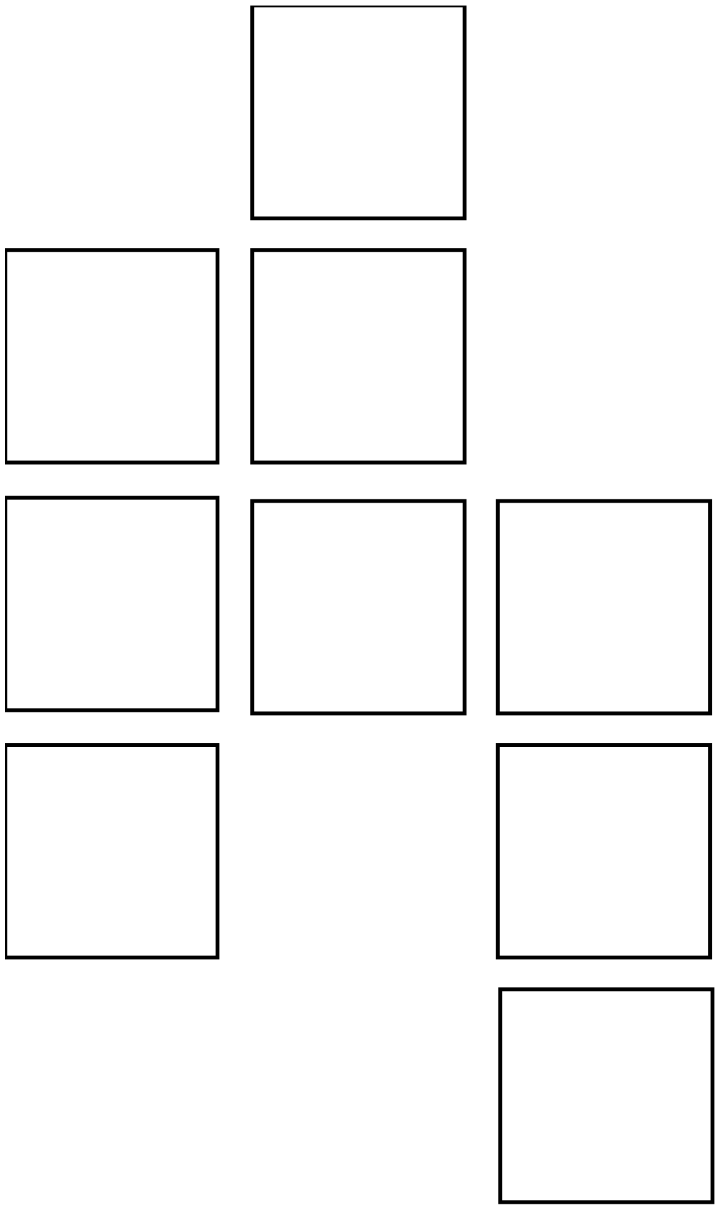
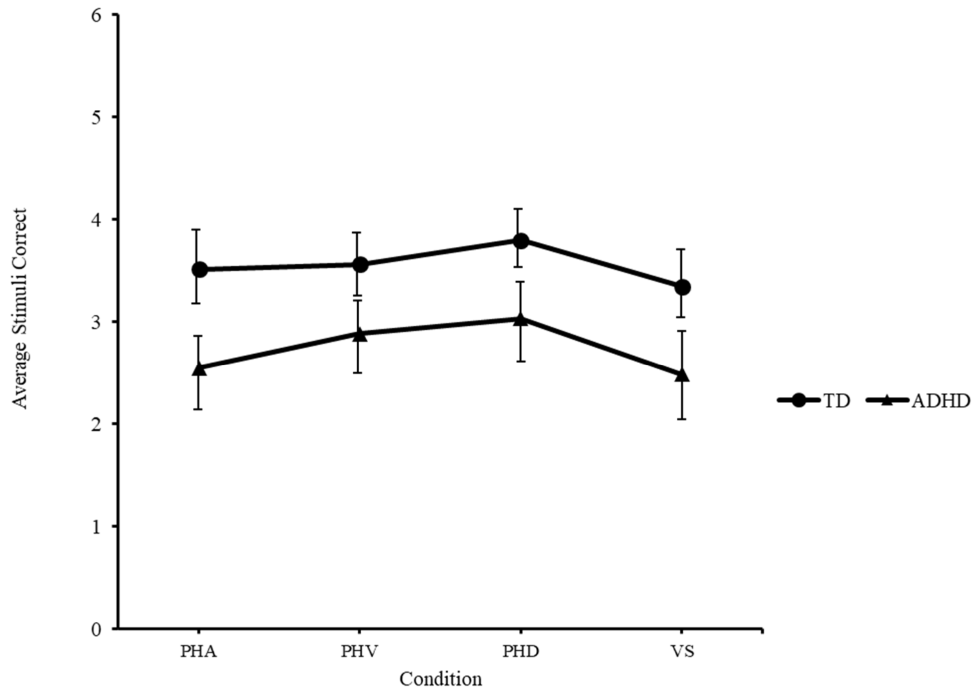
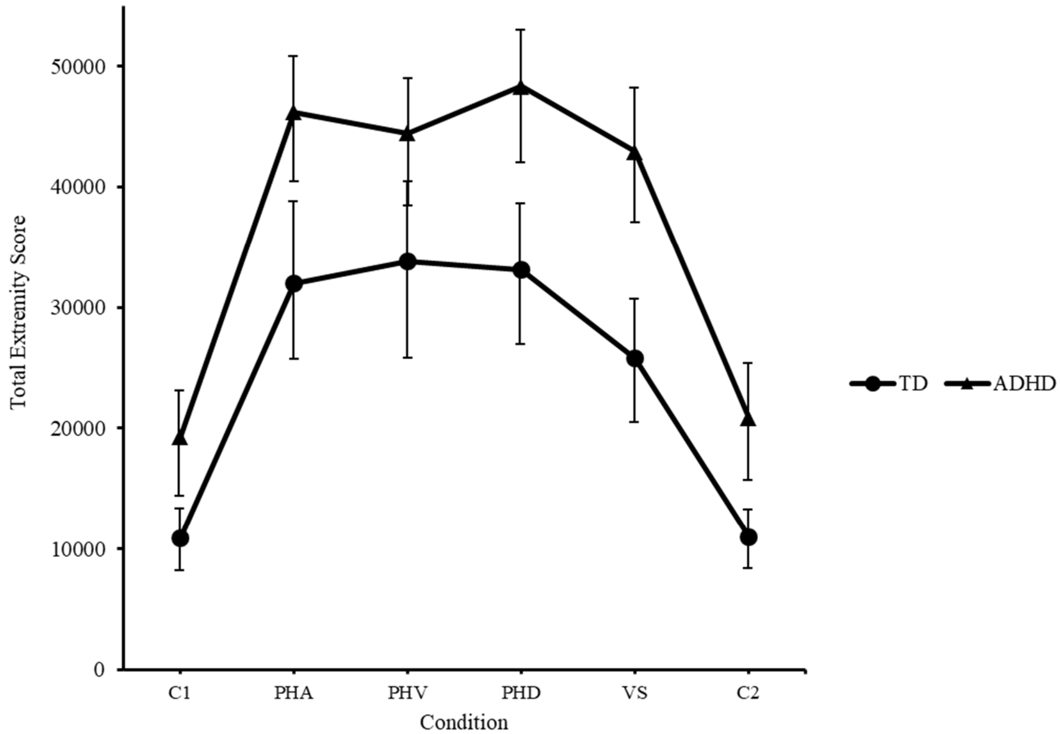


Figure 4. Performance across WM Conditions



Note. PHA= Phonological WM task, auditory presentation. PHV= phonological WM task, visual presentation. PHD= phonological WM task, dual presentation. VS= VS WM task. Error bars represent standard deviation.

Figure 5. Activity across WM and Control Conditions



Note. C1= Control condition 1. PHA= phonological WM task, auditory presentation. PHV= phonological WM task, visual presentation. PHD= phonological WM task, dual presentation. VS= VS WM task C2= Control condition 2. Error bars represent standard deviation.

APPENDIX 1

Working Memory and Motor Activity in Children with ADHD: Does Input Modality Matter?

Brief Overview

ADHD is a complex (Barkley, 2014a), highly heritable (Larsson, Chang, D'Onofrio, & Lichtenstein, 2013; Nikolas & Burt, 2010), and prevalent disorder affecting approximately 5.3% of school-aged children worldwide (Polanczyk, de Lima, Horta, Biederman, & Rhode, 2007). The disorder is characterized by inattentive, hyperactive-impulsive, or combined hyperactive-impulsive presentations (APA, 2013). ADHD is typically first noticed in childhood (Swanson et al., 1998) and is associated with negative outcomes across the lifespan, such as peer rejection (Hoza, 2007) lower levels of academic achievement (Frazier et al., 2007), lower employment attainment quality (Kessler et al., 2006), increased risk for car collisions and speeding citations (Barkley, 2014a), and increased risk for substance use (Biederman et al., 1997; Molina & Pelham, 2003).

Findings from research spanning decades have led to the development of numerous theoretical and empirically-based models of ADHD, but there is a general lack of consensus within the field concerning possible cognitive underpinnings of ADHD. Attempts to explicate the mechanisms of ADHD have led to models specifying inhibition (Barkley, 1997; Sonuga-Barke, 2005), cognitive-energetic dysfunction (Sergeant, 2000), delay aversion (Sonuga-Barke, Bitsakou, & Thompson, 2010), and/or non-cortical dysfunction (Halperin & Schulz, 2006) as primary causes of the disorder. These efforts have largely failed to account for the symptoms of ADHD, particularly hyperactivity, in a meaningful and testable manner (Rapport, Alderson, et al., 2008). The functional working memory (WM) model of ADHD, in contrast, addresses the limitations of previous models by providing a falsifiable account of the disorder and its associated symptoms (Rapport, Chung, Shore, & Isaacs, 2001). The functional working memory model of ADHD suggests there is a functional relationship between WM demands and motor activity such that as demands on WM increase, motor activity increases in children, adolescents, and adults with ADHD (Rapport et al., 2009). According to this model, cortical underarousal in children with ADHD leads to WM deficits, and ADHD-related hyperactivity serves as a compensatory mechanism to increase dopamine production and improve cortical arousal.

The functional WM model is based on Baddeley's (2007) WM model, which defines working memory as the manipulation and maintenance of information temporarily stored within one's mind. The model divides the WM system into four parts that includes the phonological (PH) buffer/loop, the visuospatial (VS) sketchpad, the episodic buffer (EB), and a domain-general central executive (CE). The PH buffer/loop allows for the temporary storage, rehearsal, and processing of phonological information, while the VS sketchpad has an analogous function for visuospatial information. The EB is a passive store that provides a temporary interface for the binding of information from perception, long-term memory, and within WM (e.g., binding of visuospatial and phonological information; Baddeley, 2012). The EB can also hold mental representations of newly generated concepts and ideas (e.g., visualizing a crab dancing the waltz;

Baddeley, 2012). Lastly, the CE is an attentional controller responsible for the division, switching, and maintenance of attention, interference control (i.e., limiting the access of extraneous information to WM), and the allocation of resources to the PH and VS subsidiary systems (Baddeley, 2007).

Systematic experimental investigations of the functional WM model have indicated that all children evince greater motor activity as a function of WM demand, but children with ADHD do in a manner disproportionate to typically- developing children (Alderson, Rapport, Kasper, Sarver, & Kofler, 2012; Hartanto, Krafft, Iosif, & Schweitzer, 2016; Hudec et al., 2015; Patros, Alderson, Hudec, Tarle, & Lea, 2017; Porrino et al., 1983; Rapport et al., 2009). Furthermore, extant research on working memory has revealed moderate to large magnitude deficits in PH storage/rehearsal processes, medium to large deficits in VS storage/ rehearsal processes, and large deficits in CE functioning for children with ADHD relative to typically developing children (Alderson, Rapport, Hudec, Sarver, & Kofler, 2010; Friedman, Rapport, Raiker, Orban, & Eckrich, 2017; Rapport, Alderson, et al., 2008). Most studies to date, however, have ignored the role of the EB when studying WM in ADHD. One notable exception experimentally examined the role of stimulus presentation modality and potential modality binding (i.e., EB processes) on WM performance in children with ADHD and typically developing (TD) children (Alderson, Kasper, et al., 2015), and found that children with ADHD did not benefit from multimodal binding to the same extent as their TD peers (Alderson, Kasper, et al., 2015). No studies to date, however, have examined the relationship between the EB and motor activity in children.

Further investigation of the EB construct is critical to providing a complete account of the functional role of WM in ADHD (i.e., including all components of Baddeley's multicomponent model). Relatedly, previous examinations of WM deficits in children with ADHD may have overestimated the contribution of the CE by inadvertently including EB processes in CE estimates (Alderson, Kasper, et al., 2015). Therefore, the current study has the potential to spur a re-evaluation of previous findings of WM deficits in children and adults with ADHD, such that consideration of EB processes will likely attenuate interpretations of the magnitude of previously observed between-group differences in the CE. Moreover, further investigation of the EB in affected children may prove helpful for efforts to parse components of the CE (Alderson, Kasper, et al., 2015; Miyake et al., 2000). Lastly, a more comprehensive understanding of EB processes in children with ADHD will likely have practical implications in both the classroom and clinical settings. For example, classroom learning could be enhanced by the presentation of educational materials in a manner that maximizes comprehension, and psychological treatment outcomes could be improved with personalized treatment to assist children with ADHD to better understand the nature of the disorder and to identify beneficial compensatory strategies.

The current study is the first to examine the relationship between EB processes and objectively-measured activity in children with and without ADHD. The EB will be measured through PH and VS working memory tasks. The three PH tasks will vary in stimulus presented modality (auditory, PHA; visual, PHV; dual, PHD). The PHA condition will provide an index of modality-pure PH processes, while the PHV condition is hypothesized to provide an index of phonological processes, orthographic to phonological conversion, and multimodal binding (i.e., binding of visually encoded phonological information). Potential within-group differences between the PHV and PHD conditions would provide evidence of EB processes beyond those associated with the PHV task. A VS task will also be included both as a methodological control for activity level comparison and to statistically isolate WM component processes, including PH and VS storage/rehearsal processes, the CE, and the EB. Lastly, children will complete a control condition hypothesized to place few demands on WM (drawing using the Microsoft Paint ® program) so that observed differences in activity can be compared across tasks requiring varying WM demands.

As a first step, the relationship between group (ADHD, TD), WM demands (PHA, PHV, PHD, VS conditions), and their interaction on performance will be examined. A significant interaction is expected such that children with ADHD will have disproportionately worse performance than TD children, with the largest between-group effects for the PHA condition, followed by PHV, PHD, and VS conditions. Next, the relationship between group (ADHD, TD), WM demands (PHA, PHV, PHD, VS, control conditions), and their interaction on objectively-measured motor activity will be examined. A significant interaction is predicted such that children with ADHD will exhibit a disproportionate increase in activity during the four WM conditions (PHA, PHV, PHD, VS) relative to the control conditions, with the largest between group difference expected for the PHA condition, followed by the PHV, PHD, and VS conditions. Lastly, the WM components (PH storage/rehearsal, VS storage/rehearsal, and the CE) will be isolated statistically through a regression approach and differences in activity related to EB processes will be compared between groups (ADHD, TD). Children with ADHD are hypothesized to have higher levels of EB-associated activity compared to TD children.

Overview of Attention-Deficit/ Hyperactivity Disorder

Attention-deficit/ hyperactivity disorder (ADHD) is a pervasive disorder that affects approximately 5.3% of school-aged children worldwide (Polanczyk et al., 2007) and is characterized by difficulties with inattention, hyperactivity, and impulsivity. ADHD is associated with significant social and academic impairment (Hoza, 2007; Frazier et al., 2007, respectively) and numerous maladaptive outcomes such as lower occupational functioning (Brook, Brook, Zhang, Seltzer, & Finch, 2013; Klein et al., 2012) and greater risk for adolescent substance use (Molina & Pelham, 2003). Furthermore, 80% of individuals with ADHD are diagnosed with at least one other comorbid disorder (Barkley, Murphy, & Fisher, 2008).

Although ADHD prevalence rates in children range from about 5% to 7% in the United States (Polanczyk et al., 2007), there is significant variability in these estimates, largely attributable to heterogeneity in study methodology (e.g., sample characteristics, diagnostic procedures utilized; Polanczyk, Willcutt, Salum, Kieling, & Rohde, 2014). For example, some studies report estimated prevalence rates without using proper diagnostic procedures (i.e., relying on the use of a single rating scale or only utilizing one rater; Roberts, Milich, & Barkley, 2015). In these cases, estimated prevalence rates are higher than estimates derived from studies that require evidence of symptoms across multiple settings (Skounti, Philalithis, & Galanakis, 2007). Furthermore, the ratio of boys to girls included in a sample can affect reported rates, as studies that include a greater percentage of girls are frequently associated with lower reported prevalence rates (Ramtekkar, Reiersen, Todorov, & Todd, 2010). Lastly, the age of the sample can negatively impact prevalence estimates, due to an age-dependent decline (Faraone, Biederman, & Mick, 2006) in the persistence of ADHD and corresponding symptom display.

There are three presentations of ADHD (formerly referred to as subtypes, DSM-IV-TR, American Psychiatric Association, APA, 2000): predominately inattentive presentation, predominately hyperactive-impulsive presentation, and combined presentation (APA, 2013). The predominantly inattentive presentation of ADHD is characterized by absentmindedness, daydreaming and/or mind wandering. For children, the predominantly inattentive presentation of ADHD may manifest behaviorally as careless errors in schoolwork (e.g., forgetting to watch the computational signs on arithmetic problems), not following through on activities despite having understood the instructions, difficulties with organization, and losing things necessary for tasks or activities (e.g., forgetting to bring completed homework back to school; APA, 2013). In contrast, the predominately hyperactive/impulsive presentation of ADHD is characterized by behaviors such as excessive motor activity and impulsive responding. For example, children with the hyperactive/impulsive presentation of ADHD frequently squirm in their seat and run or climb in situations where it is inappropriate, such as the classroom. Additionally, they may act as if they are 'on the go' or driven by a motor, blurt out answers, interrupt others, or struggle with waiting their turn. The combined presentation of ADHD is associated with difficulties in both attention and hyperactivity/impulsivity (APA, 2013).

These separate presentations are supported by factor analytic research. Specifically, factor analytic studies have most commonly identified measurement models with two specific factors that reflect inattentive and hyperactive-impulsive symptom domains (Wilcutt, 2012). Findings from confirmatory factor analyses have consistently exhibited superior model fit with a single factor reflecting hyperactivity and impulsivity, rather than one factor representing hyperactivity and one factor representing impulsivity (Martel, von Eye, & Nigg., 2010; Toplak et al., 2012; Wilcutt, 2012; Wolraich et al., 2003). That is, models specifying three factors of inattention, hyperactivity, and impulsivity do not demonstrate significantly better fit than models where hyperactivity and impulsivity are combined into a single factor. Several models tested within these studies identify two specific factors (inattentive and hyperactive-impulsive) and allow the two specific factors to correlate, rather than constraining them to be orthogonal (Van Eck, Finney, & Evans, 2010; Wolraich et al., 2003). In contrast, other researchers have identified a hierarchical or bifactor model in which all items load onto a general ADHD factor, as well as onto specific inattentive and hyperactive-impulsive factors (Dumenci, McConaughy, & Achenbach, 2004; Martel, Roberts, Gremillon, von Eye, & Nigg, 2011; Martel et al., 2010; Martel von Eye, & Nigg, 2012; Toplak et al. 2012). This link between the inattentive and hyperactive-impulsive symptom domains is consistent with studies finding elevated objectively-measured motor activity across all presentations of ADHD, not just the hyperactive/impulsive presentation (Bauermesiter et al., 2005; Dane, Schachar, & Tannock, 2000; Hartanto et al., 2015; Miyahara, Healey, & Halperin, 2014). The DSM-5 (APA, 2013) conceptualization is consistent with a two-factor model where inattention and hyperactivity-impulsivity factors are correlated (Ghanizadeh, 2012; Tannock, 2012).

Sex Differences

ADHD is more common in males than females, whether based on formal diagnoses (3.2 males:1 female; Willcutt, 2012), symptom counts (2.43:1; Arnett, Pennington, Willcutt, DeFries, & Olson, 2015), community samples (2.3:1; Bauermeister et al., 2007; Ramtekkar et al., 2010; 3:1, Szatmari, Offord, & Boyle, 1989), or clinic-referred samples (10:1; Biederman et al., 2002). These sex differences can be magnified by sample characteristics (community vs. clinic-referred, age of subjects) and diagnostic procedures ('gold standard' diagnostic approach vs. symptom counts; Gaub & Carlson, 1997). Compared to community samples, samples of clinic-referred children with ADHD have significantly higher rates of boys relative to girls. This discrepancy reflects a referral bias where parents and teachers are more likely to identify problematic behaviors in boys with ADHD, compared to girls with ADHD, because boys with ADHD display more hyperactive and externalizing behaviors relative to girls with the disorder (Gaub & Carlson, 1997). Furthermore, boys are more likely to be clinic-referred for learning disorders and subsequently be identified as having ADHD, contributing to the greater representation of boys versus girls within clinic samples (Biederman et al., 2002).

Although fewer girls with ADHD are clinic-referred relative to boys with ADHD, girls who are referred often demonstrate greater impairment in inattention than their male counterparts (Gaub & Carlson, 1997; Gershon, 2002). This is consistent with findings that girls are 2.2 times more likely to be diagnosed with the inattentive presentation than the hyperactive/impulsive presentation, at least in a clinic-referred sample (Biederman et al., 2002). However, in non-referred samples, these gender differences in presentation attenuate such that males and females are equally likely to meet diagnostic criteria for any presentation of ADHD (Graetz, Sawyer, & Baghurst, 2005; Biederman et al., 2005).

Few studies have explicitly measured sex differences in hyperactivity and frequency, and no studies have done so using objective measures of hyperactivity. Rating scale research indicate that, as a group, boys with ADHD are rated more hyperactive than girls with the disorder (Arnett et al., 2015; deHaas, 1986; Gaub & Carlson, 1997; but see Horn, Wagner, & Ialongo, 1989; James & Taylor, 1990 for exceptions). Further, a multisite study using an established coding scheme revealed variable patterns in observed classroom activity across genders (Abikoff et al., 2002), such that boys with ADHD demonstrated more gross motor movements (e.g., leaving seat without permission, running, skipping) and were out of their chair for an extended time (i.e., more than 15 seconds) more often than girls with ADHD. However, boys and girls with ADHD had equal rates of observed minor motor behaviors (squirming or rocking in seat). When compared to their typically developing same gender peers, boys with ADHD demonstrated more minor motor movements, gross motor movements and out of seat behavior, while girls with ADHD exhibited more minor and gross motor movements, but equal rates of out of chair behavior (Abikoff et al., 2002). Lastly, a recent meta-analytic review (Kofler, Raiker, Sarver, Wells, & Soto, 2016) found that studies with samples comprised of fewer than 25% females had significantly larger effect sizes than studies with greater than 25% females in their sample.

History of ADHD and Hyperactivity in ADHD

The nomenclature used to describe ADHD has developed in accordance with changing conceptualizations of the disorder (e.g., *the brain injured child*, Strauss &

Lehtinen, 1947; *minimal brain damage*, Barkley, 2014b; *minimal brain dysfunction*, Barkley, 2014b; and *hyperkinetic impulse disorder*, Laufer et al., 1957), and as implied by these changes, the role of hyperactivity in the conceptualization of ADHD has waxed and waned. Melchior Adam Weikard in the 1770's, first described an illness characterized as a lack of attention (Barkley & Peters, 2012).

In the eighteenth and nineteenth century, several scholars wrote detailed accounts about ADHD-related symptoms, describing disorders of distractibility and low energy (Chrichton, 1798), fidgety children (Hoffman, 1865), problems with moral control (James, 1890), mentally unstable children (Bourneville, 1895), and impulsive children with learning problems (Clouston, 1899). George Frederic Still suggested that children afflicted with this syndrome had defects of "cognitive relation to environment," "moral consciousness," and "inhibitory volition" (Still, 1902). Similarly, Tredgold described low-intelligence children with poor attention, impulse control, and willpower (1908).

In the late 1910's (1917-1918), an epidemic of encephalitis in North America led to a surge of survivors with cognitive and behavior problems similar to symptoms of what is now termed ADHD and oppositional defiant disorder (ODD). The increased incidence of these cognitive and behavioral difficulties precipitated an increased interest in scientific attention to their possible etiologies. Measles, lead poisoning, epilepsy, and head injuries were identified as possible brain-related antecedents to attention problems (Barkley, 2014b).

By 1947, scholars Strauss and Lehtinen were using the term *brain-injured child* to describe children with ADHD-like symptoms, and asserted that behavioral or cognitive problems alone were necessary evidence of brain injury (Strauss & Lehtinen, 1947). The moniker changed to *minimal brain damage* (Kessler, 1980; Ross & Ross, 1976) and later *minimal brain dysfunction* (Clements & Peter, 1962; Loney, Langhorne, & Paternite, 1978) because research of that time did not reveal evidence of brain injury (Laufer et al., 1957). A host of studies in the late 1950's and early 1960's (Chess, 1960; Birch, 1964; Herbert, 1964; Rapin, 1964) led to the renaming of these symptom clusters to *hyperactivity syndrome*. In 1968, this hyperactivity syndrome appeared in the second edition of the Diagnostic and Statistical Manual of Mental Disorders (DSM) as *hyperkinetic reaction of childhood disorder*.

In the 1970's, the role of hyperactivity in explaining the symptoms of the disorder was less emphasized relative to sustained attention and impulse control, in no small part due to Virginia Douglas's presidential address to the Canadian Psychological Association (1972). In 1980, Douglas introduced a model of attention deficits with four deficits accounting for symptoms: ineffective maintenance of attention and effort, a failure to inhibit impulsive responses, situation-incongruent arousal levels, and abnormally heighted propensity for immediate rewards. While certainly influential, the model did not hypothesize the relationships among deficits or how they caused specific symptoms and consequently, was non-falsifiable. Nonetheless, Douglas's work contributed to the naming of "attention deficit disorder (ADD)" in the DSM-III (APA, 1980), in which children could be diagnosed as meeting criteria for ADD with or without hyperactivity.

The conceptualization of the disorder was again revised in the DSM-III text revision (DSM-III-TR; APA, 1987) such that the diagnosis did not include subtypes, recognizing the scarce empirical evidence at the time supporting the existence of ADHD subtypes (Lange, Reichl, Lange, Tucha, & Tucha, 2010). Specifically, in the revision, there was one disorder termed ADD, and ADD without hyperactivity was moved to the category of “undifferentiated ADD” (Lange et al., 2010).

Accumulating evidence after the publication of the DSM-III-TR indicated that there were indeed differences between symptoms of the disorder with and without hyperactivity (e.g., inattention characterized by lethargy, daydreaming, greater peer acceptance relative to the hyperactive subtype; Barkley, Grodzinsky, & DuPaul, 1992; Carlson, 1986; Lahey & Carlson, 1992). The reification of the disorder in the DSM-IV (1994) included three subtypes (inattentive, hyperactive-impulsive, and combined) and introduced the term ADHD. The DSM-IV-TR (2000) made no significant organizational changes from the DSM-IV. Subtypes were renamed as presentations in the most recent iteration of the DSM in order to reflect the temporal instability of the symptom clusters (DSM-5; Lahey, Pelham, Looney, Lee, & Willcutt, 2005; Tannock, 2012). The required age of onset was also changed from 7 years to 12 years, to reflect the difficulty of retrospective recall by adults. Lastly, one fewer symptom is required for a diagnosis in adolescents and adults compared to children, reflecting the attenuation in symptoms over time (Faraone, Biederman, et al., 2006; Solanto, Wasserstein, Marks, & Mitchell, 2011). The DSM-5 does not specify the pervasiveness or, conversely, environmental specificity (i.e., levels of stimulation and cognitive demands), in its conceptualization of hyperactivity, which is defined in the DSM as situationally inappropriate excessive motor output or excessive minor motor activity (APA, 2013).

Activity Research Methods

Parent, teacher, and/or self-report ratings scales are the most commonly used method to assess ADHD-related motor activity (Rapport, Kofler, & Himmerich, 2006).

Findings from studies that utilized rating scales suggest that children with ADHD display more motor activity than children without ADHD (Bell, Waldrop, & Weller, 1972; Wachbusch, 2002). Further, parent and teacher reported ratings of ADHD-related hyperactivity are significantly correlated with later academic achievement (Fergusson, Lynskey, & Horwood, 1997) and adult criminal activity (Babinski, Hartsough, & Lambert, 1999).

While ratings scales are easy to administer and low-cost, they require the rater to average perceptions of behavior across time to create global judgements and typically do not consider variation in activity according to task (Rapport et al., 2006). Furthermore, extant findings suggest that rating-scale metrics of motor activity poorly correlate with objective measures of activity (Dane et al., 2000; Rapoport, Abramson, Alexander, & Lott, 1971; Rapport et al., 2006; Stevens, Kupst, Suran, & Schulman, 1978; Tryon & Pinto, 1994). A similar trend for non-rating scale measures has also been detected, with interview items evincing limited convergent validity with objective measures of activity (Dane et al., 2000).

There are several objective measures of activity, which fall under two main categories of behavior coding and physical instruments. Behavior coding involves recording the number of steps taken, the number of times a grid on the floor is crossed (Partington, Lang, & Campbell, 1971), or more complex movements, such as fidgeting, upper limb movements, head movements, and/or whole body movements (Konofal, Lecendreux, Bouvard, & Mouren-Simeoni, 2001; Whalen, Henker, Collins, Finck, & Dotemoto, 1979). Although these methods can provide basic information about gross motor activity, they are labor-intensive and provide spatially-limited information about activity (Halverson & Waldrop, 1973). That is, the activity information gathered from behavior coding methods is limited to the specific physical area being coded. Further, the accuracy of observational methods is susceptible to procedural drift, unlike physical instruments (Rapport et al., 2006).

Physical instruments for objectively measuring activity include pedometers, actometers, and actigraphs. There are few studies utilizing pedometers, which purportedly measure the number of steps taken, with children with ADHD; however, Plomin and Foch (1981) found that locomotion (activity) measured by weeklong pedometer use was not elevated in hyperactive children relative to comparison children. Actometers record frequency of movement by detecting changes in direction along the instrument (Bell, 1968; Rapport et al., 2006), and are more sensitive than pedometers in measuring activity level and differentiating TD and ADHD groups of children (Barkley & Ullman, 1975; Rapoport et al, 1971). However, actometers do not provide information about duration or intensity of movement and can only report average frequencies (Rapport et al, 2006). The test- retest reliability of actometers ranges from .33 to .92, depending on the length of time between testing and the sample size (Halverson & Woldrop, 1973; Massey et.al, 1971; Tryon, 2008).

In contrast, actigraphs provide information regarding frequency, intensity, and duration of movement by generating a current each time they are moved (Tyron, 1991). Actigraphs have multiple settings that can be used to modify sampling rates and the length of time over which to average data samples, which allows researchers or clinicians to specify the balance they wish to strike between specificity and duration of recorded movements. Sampling rates refer to the number of samples collected per second and are measured in hertz (Hz). The samples are combined into one data point for a specific unit of time, called an epoch. There is a direct relationship between epoch length and data specificity such that as epoch length shortens, the data becomes more specific. For example, an actigraph set at a 10-Hz sampling rate with a 10-minute epoch that collects data over a continuous 60-minute period would yield six data points that were each based on 600 epoch samples. If the epoch length were shortened to one minute and the sampling rate and data collection period remained the same, then the actigraphs would yield 60 data points, where each point is based on 60 epoch samples (Rapport et al., 2006). This flexibility in settings allows users to employ actigraphs in a precise and detailed manner.

The placement of actigraphs can affect measured activity rates such that an actigraph placed around the waist, for example, is more appropriate for large-scale movements than for small-scale movements such as fidgeting (Rapport et al., 2006). While actigraph site does not limit detection of gross body movements, finer-grained body movements may only by detected by actigraphs worn on extremities (e.g., wrists or ankles; Tryon, 2011). In addition to the variety of placements, there are also different types of actigraphs detection.

Actigraphs allow for great versatility in their different detection modes. For example, the MicroMini Motionlogger brand of actigraphs can be set to one of three modes: Zero Crossing, which measures only frequency of movement, low Proportional Integrating Measure (PIM), which measures intensity of movement, and high PIM, which doubles the transduction signal and therefore provides a measure of movement intensity that is appropriate for infants or individuals with highly restricted range of motion

(Ambulatory Monitoring, 2010). Actigraphs have been commonly used in ADHD research (Rapport et al., 2006), sleep research (Morgenthaler et al., 2007), and exercise science (Tryon, 2011).

Actigraphs typically have a large memory that can record information over several weeks (Rapport et al., 2006) and the test-retest reliability of actigraphs is very high (.90 to .99; Tryon, 1991). Collectively, research on activity measurement point toward actigraphs as the best option for simple, straightforward measurement of activity level (Barkley & Ullman, 1975; Dane et al., 2000; Halverson & Waldrop, 1973; Rapoport et al., 1971; Rapport et al., 2006; Stevens et al., 1978; Tyron, 1991; Tryon & Pinto, 1994).

Models of ADHD

Inhibition

Barkley's (1997) unified theory of ADHD borrows from aspects of Quay's (1997) explanation of ADHD in terms of behavioral inhibition and behavioral activation systems, based on Logan and Cowan's horse race model of inhibition (Logan & Cowan, 1984; Schachar & Logan, 1990), which expanded on Gray's (1982) explanation of anxiety using the concept of an underactive behavioral inhibition system. Barkley's model posits that the central deficit of the hyperactive or combined presentation of ADHD is poor behavioral inhibition, which is defined as three overlapping and interrelated processes: the stopping of an initial response to an event, the stopping of an ongoing response, and the sustainment of a delay period that provides a context for self-directed responses (Barkley, 1997). Importantly, the stopping of an ongoing response permits a delay in the decision to respond and therefore allows for interference control (Barkley, 1997).

According to Barkley's model, deficits of behavioral inhibition lead to deficits in four executive functions (EFs): working memory, self-regulation, internalization of speech, and reconstitution (i.e., behavioral analysis and synthesis). Notably, behavioral inhibition provides a context for the enactment of executive function. Therefore, when operating in a context of optimal behavioral inhibition, these four EFs allow for purposeful, goal-directed behavior enacted by the motor control-fluency-syntax component of the model. In the context of suboptimal, deficient behavioral inhibition, there is no opportunity (i.e., delay period) for the enactment of executive function. Therefore, working memory, self-regulation, internalized speech, and reconstitution cannot work together to deftly guide behavior in an organized, directed fashion. Failure of these EFs leads to behaviors such as poor control of motor behavior (i.e., hyperactivity), inconsistent responding to environmental stimuli, and frequent lapses in attention. Importantly, Barkley's model views hyperactivity as a ubiquitous feature of the disorder where motoric output is highly linked to an individual's immediate surroundings, rather than motoric output being related to internalized representations of desired future outcomes. That is, the model predicts that behavior of children, adolescents, and adults with ADHD is guided more by in-the-moment, immediate stimuli than by consideration of the positive outcomes of completed goals.

Cognitive-energetic

Sergeant's (2000) cognitive-energetic model (CEM) of ADHD challenges the central role of inhibition within the disorder and instead explains ADHD-related deficits within the framework of Sanders' (1983) general cognitive-energetic model. ADHD deficits are related to each of three levels of the CEM (Sergeant, 2005). The first level, *information processing*, is composed of encoding, central processing (i.e., search and decision), and motor organization. ADHD is directly related to the motor organization component (Sergeant, 2000, 2005) of this first level. Support for this assertion is provided in an earlier study that suggests children with ADHD, relative to TD children, exhibit delayed response time (van der Meere, Vreeling, & Sergeant, 1992). However, the connection between motor organization and response time is unclear in the studies cited for the model. The second level of the CEM consists of energetic pools of arousal, activation, and effort. The *arousal pool* corresponds to preparedness to receive information, the *activation pool* relates to physiological activity, and the *effort pool* represents the necessary energy for performing a task (Sergeant, Oosterlaan, & van der Meere, 1999). The *effort pool* is related to concepts such as motivation and contingent responses (Sergeant, Oosterlaan, & van der Meere, 1999). Both the *activation* and *effort pools* jointly affect motor output and are relevant to ADHD-related hyperactivity and impulsivity (Sergeant, 2000). Lastly, the third level, *the management or evaluation mechanism*, encompasses processes commonly described as executive function (Sergeant, 2000). This level involves planning, monitoring, error detection, and error correction.

A weakness of this model is its vague and difficult-to test predictions, albeit extant studies have attempted to integrate previous empirical work into support for specific model hypotheses (e.g., interpreting impulsivity as evidence of problems with the effort energetic pool and adjusting motivational states; Sergeant, 2000, 2005). There are no current measures, however, that assess the precise constructs of the energetic pools. Further, the model does not explain the role of hyperactivity within ADHD or provide any testable predictions regarding the purpose of elevated motor activity (Rapport et al., 2009).

Delay Aversion

Sonuga-Barke's tripartite model of ADHD posits multiple distinct pathways leading to the ADHD phenotype: inhibition deficits, temporal processing deficits, and delay aversion (Sonuga-Barke et al., 2010). Inhibition deficits refer to difficulties with the withholding or stopping of a prepotent motor response (i.e., difficulties associated with behavioral inhibition, similar to Barkley's 1997 explanation), and temporal processing deficits refer to difficulty estimating the passage of time (usually overestimation). Delay aversion is defined as a negative emotional reaction to periods of delay and suboptimal interaction with delay-heavy environments. It is a biologically based phenomenon in which future rewards are less valued relative to more immediate rewards (Sonuga-Barke, 2003). Each of these impairments (inhibition deficits, temporal processing deficits, and delay aversion) corresponds to dissociable neuropsychological components that may independently or in combination lead to the development of ADHD (Sonuga-Barke, 2005; Sonuga-Barke et al., 2010). Thus, individuals with ADHD may display deficits in one, two, or all three of the aforementioned pathways. Hyperactivity is explained as a result of efforts to shorten the perceived length of the delay by further interacting with environment (Sonuga-Barke, 2005).

There are several studies supporting the discreteness of inhibition deficits, delay aversion, and timing (Solanto et al., 2001; Sonuga-Barke et al., 1994; Sonuga-Barke et al., 2010). Additionally, there is empirical evidence for increased activity during long delays, as predicted by the model (Antrop, Buysse, Roeyers, & Van Oost, 2005).

However, the model does not specify how inhibition or temporal processing deficits would lead to hyperactivity.

Neurodevelopmental

Halperin's (2006) neurodevelopmental model suggests that that ADHD-related neural dysfunction in noncortical areas (i.e., subcortical structures, midbrain) arises early in development and remains constant across the lifespan (Halperin & Schulz, 2006). Because this dysfunction remains constant, any reduction in ADHD symptomatology is the result of greater prefrontal control minimizing the effect of non-cortical neuronal dysfunction, rather than the prefrontal cortex directly causing any symptom remission. That is, dysfunction of the prefrontal cortex (PFC) does not directly lead to the ADHD phenotype.

Certain components of the neurodevelopmental model are empirically supported. For example, the hypothesis that the PFC cannot play a central role in the etiology and development of ADHD is supported by the presence of ADHD symptoms before full maturation of the PFC (Halperin & Schulz, 2006). Additionally, Halperin and Schulz (2006) argue that if EF deficits solely account for ADHD, then those deficits should be universally found in children with ADHD. However, across studies, some children with ADHD do not demonstrate EF deficits (Berwid, Kera, Santra, Bender, & Halperin, 2005; Marks et al., 2005), which Halperin interprets as evidence that ADHD must result from something other than EF deficits. Recent research, however, has provided important insights into why these inconsistencies in presence and magnitude of EF deficits have been observed. Specifically, meta-analytic research with both children and adults indicates that sample (i.e., percent female, age of children) and methodological (i.e., number of trials within a task, tasks requiring recognition of stimuli versus recall of stimuli) characteristics contributed to heterogeneity in effect sizes across studies, and studies that utilize best-case procedures are expected to yield large-magnitude effect sizes of 1.22 to 2.15 for VS WM and and 1.44 to 2.01 for PH WM (Kasper, Alderson, & Hudec, 2012; Alderson, Kasper, Hudec, & Patros, 2013). Furthermore, a recent experimental (Tarle et al., 2017) study revealed that the utilization of best-case scoring procedures (e.g., partial versus absolute scoring, discontinue rules) and task characteristics (number of trials per task set size, extent to which tasks tax working memory) resulted in larger between-group effect sizes for children with ADHD and typically-developing children.

Collectively, findings from these studies undermine the scant research support for Halperin's (Halperin & Schulz, 2006) neurodevelopmental model. Additionally, the model does not specify the etiology of the noncortical dysfunction thought to underlie all ADHD development, nor does it provide any testable hypotheses regarding the impact of neural dysfunction on ADHD- related motor activity in children.

Working memory

Recent studies have called into question the central role of behavioral inhibition, energetics, delay aversion, and noncortical dysfunction in ADHD, and instead suggested that those hypothesized mechanisms may be secondary to and underpinned by deficits in working memory (e.g., Alderson et al., 2010; Rapport et al., 2008). These recent findings are consistent with Rapport and colleagues' functional working memory model, which is based on Baddeley's (2000) multicomponent working memory model. Briefly, Baddeley's multicomponent working memory model is comprised of four components: a domain-general attention controller (the central executive; CE), two domain-specific subsystems, and a passive store for bound information from multiple modalities (episodic buffer, EB). The domain-specific subsystems are the phonological storage/rehearsal loop and the visuospatial sketchpad. Each of these are responsible for temporary storage and rehearsal of their respective information. More detailed explanations of Baddeley's model and Rapport's functional working memory model of ADHD are provided below.

Baddeley's Working Memory Model

Baddeley defines working memory as a limited capacity temporary store that is responsible for the storage and manipulation of information (Baddeley, 2000, 2007). The multicomponent working memory model includes a domain-general central executive (CE), a phonological (PH) buffer/ loop, a visuospatial (VS) sketchpad, and an episodic buffer (EB; Baddeley 2000). The CE serves as an attentional controller that guides the allocation of resources to the subsidiary PH buffer/loop and VS sketchpad. The CE can be viewed as the "working" component of working memory that governs the short-term memory responsibilities of the PH buffer/ loop and VS sketchpad (Baddeley, 2007). That is, the CE is responsible for coordinating the actions of the subsidiary systems, dynamically allocating resources to those systems, manipulating information within them, and communication between working and long-term memory (Baddeley, 2007). Lastly, the CE manages controlled-focused attention and interference control (i.e., limiting non-essential information from accessing WM), and is responsible for the division, switching, and maintenance of attention (Baddeley, 2007).

The PH buffer/loop temporarily stores verbal information through the use of a phonological buffer and an articulatory rehearsal system (Baddeley, 2000). The PH buffer holds phonological information, which decays in memory after approximately two seconds (Baddeley, 2007). The PH loop allows for subvocal rehearsal of the information stored in the buffer, which refreshes the memory trace (Baddeley, 2007). Evidence for the PH buffer/loop is provided by the articulatory suppression effect (Murray, 1968), wherein people have poorer recall for verbal stimuli when they are required to verbalize other sets of words. Articulatory suppression is thought to interfere with subvocal rehearsal processes. The irrelevant speech effect, where hearing unrelated sounds from other sources disrupts recall of information (Colle & Welsh, 1976, Salamé & Baddeley, 1990), and the phonemic similarity effect, in which words that sound similar are more difficult to remember than words that sound dissimilar (Conrad & Hull, 1964), also provide support the use of subvocal rehearsal within the PH buffer/loop. Further, the PH buffer/loop appears to have an essential role for language comprehension. Evidence for this arises from adult participants with short-term PH deficits who can understand short, simple sentences, but are unable to comprehend complex, longer sentences (Vallar & Baddeley, 1987).

Like the PH buffer/loop, the VS sketchpad provides for temporary storage of visual and spatial information. Extant evidence indicates that visual and spatial WM are independent (Klauer & Zhao, 2004; Smith & Jonides, 1997), and haptic perception is theorized to be a part of the VS sketchpad (Baddeley, 2012). Neuroimaging research suggests that brain areas activated when perceiving an object are the same as those activated when employing the VS sketchpad (e.g., rotating objects in one's mind; Broggin, Savazzi, & Marzi, 2012). Evidence for independence between the PH and VS systems is supported by factor-analytic research (Alloway, Gathercole, & Pickering, 2006), neuroimaging studies (Fassbender & Schweitzer, 2005, Smith, Jonides, & Koeppe, 1996), and the lack of an articulatory suppression effect for the VS sketchpad (Baddeley, 2012).

The episodic buffer (EB) is a passive store that holds bound information from multiple modalities (Baddeley, 2012). It is termed “episodic” because it integrates pieces of information into consciously accessible, chunked episodes of information. The “buffer” portion of the term refers to the combined information from systems assumed to have separate, multimodal codes (Baddeley, Allen, & Hitch, 2010). The binding process can involve integrating information from the WM subsystems (i.e., PH loop or VS sketchpad), long-term memory, or sensory input (Baddeley, 2007; Baddeley, Allen, & Hitch, 2010), and includes information such as multiple features of an object (color, size, brightness, movement) or words bound into a sentence (Baddeley, 2012). Notably, the binding of information is realized outside of the EB and is largely independent of WM itself (Baddeley, Allen, & Hitch, 2010; Baddeley & Wilson, 2002; Gooding et al., 2005). Although the EB is not responsible for the act of binding, in allowing access to the bound information, it frees executive resources for further manipulation of sensory input (Baddeley, 2012; Baddeley, Allen, & Hitch, 2010).

Support for the EB construct is provided by numerous studies examining the EB across various domains. Within the visuospatial arena, a series of carefully controlled studies have explicated that memory for objects with multiple features does not necessitate more working memory use than does memory for objects with single features. For example, on tasks requiring participants to judge the presence or absence of a stimulus after viewing an array of stimuli of various colors, shapes, or colored shapes, participants were equally able to identify the stimulus when it was in a set of four stimuli, regardless of whether they were viewing colors, shapes, or colored shapes (Luck & Vogel, 1997; Vogel, Woodman, & Luck, 2001). Vogel and colleagues (2001) demonstrated through additional studies that the observed performance equivalency was not due to verbal coding of stimuli, a cumulative effect of errors in decision making, or faulty encoding processing, but was instead due to the storage of "integrated object representations" (p.109) within visual working memory. Many other studies have found the same performance equivalency for multi vs. single feature object retention in working memory (Allen, Hitch, Mate, & Baddeley, 2012; Karlsen, Allen, Baddeley, & Hitch, 2010; Wheeler & Treisman, 2002). Evidence for the EB within visual working memory has also been applied to the binding of objects into chunks (Rossi-Arnaud et al., 2006).

There are fewer examinations of the EB within the verbal realm, but the extant research provides support for the EB construct. For example, the visual similarity effect, in which recall is poorer for words that look and sound alike compared to words that only sound alike, suggests that visually presented information must be stored in either a visual and phonological code or a multimodal code (Logie, Della Sala, Wynn, & Baddeley, 2000). Other studies have largely focused on sentence recall (Baddeley, Hitch, & Allen, 2009) and examine the sentence superiority effect, where memory for sentences is better than memory for random word lists (Baddeley et al., 2009). This effect in itself provides evidence for the EB, in that the improved memory is likely a result of interaction between short-term storage and long-term memory of language structure (Baddeley et al. 2009). Rudner and colleagues (2007) examined the potential role of EB processes in a neuroimaging study of individuals fluent in Swedish and Swedish sign language since birth. They found activation in specific posterior regions of the brain during a task requiring binding of language units (Rudner, Fransonn, Ingvar, Byberg, & Rönnberg, 2007). These brain regions were distinct from areas associated with sign language and speech processing.

Although the EB has been studied less often in children relative to adults, evidence for the presence of the EB in typically-developing young children is growing (Alloway, Gathercole, Willis, & Adams, 2004; Wang, Allen, Lee, & Hsieh, 2015). For example, Wang and colleagues (2015) studied the development of the EB in relation to word recognition in a sample of children aged 8 to 9 years. Children completed a working-memory binding task that first presented sequences of non-words and abstract shapes. The task subsequently presented one feature (i.e., non-word or shape) of the to-be-remembered sequence and asked the children to identify the corresponding feature from a set of eight possible options. Findings from the study suggest that binding (proportion of correct responses among the two and three item sequence lengths) was more proficient in older children. Binding was also a unique predictor of word recognition skills after statistically controlling for the contribution of children's age, phonological ability, naming speed ability, and memory for individual features.

Findings from structural equation modeling research have also provided support for the EB construct in typically-developing children (Alloway et al., 2004). Children completed a variety of tasks hypothesized to measure the EB, complex memory, phonological short-term memory, and nonverbal ability, and several measurement models were compared. The models differed in structure and theoretical basis (e.g., one model was based on the results of exploratory factor analysis, another was a one-factor model based a theory of unitary WM, another was based on Baddeley's multicomponent WM model). The best fitting and most parsimonious model included individual factors for the CE (the complex memory span tasks), the EB (sentence repetition tasks), the PH buffer/loop (phonological short-term memory tasks), phonological awareness (phonological awareness tasks), and visual spatial ability (termed nonverbal ability and represented by Block Design and Object Assembly scores from the WPPSI; Wechsler, 2002). Although this study provides insight into an understudied construct, a number of methodological flaws weakens its findings. Specifically, many of the tasks employed in the study were designed for ages 5 to 8, even though the sample included children under age five. Further, the tasks were scored with an absolute scoring procedure, which captures a narrow view of children's abilities and may have skewed the performance distribution (Unsworth & Engle, 2007; Conway et al., 2005). Lastly, the study's CE task (a backwards digit span task) likely placed few demands on CE processes (Moleiro et al., 2013; Engle, Tuholski, Laughlin, & Conway, 1999).

Functional Working Memory Model of ADHD

Rapport and colleagues' functional working memory model suggests that hyperactive, impulsive, and inattentive symptoms of ADHD are functionally related to variability in working memory demands (Rapport et al., 2001; Rapport et al., 2009). Specifically, cortical underarousal and underdeveloped working memory lead to the core behavioral symptoms of ADHD (inattention, hyperactivity, impulsivity). Thus, cortical underarousal and undeveloped working memory represent the ADHD endophenotype, while the behavioral symptoms and functional impairments (e.g., behavioral disinhibition, disorganization, and impaired social and academic functioning) represent the ADHD phenotype (Rapport, Alderson, et al., 2008).

The model hypothesizes that neurobiological substrates lead to working memory and arousal deficits. These deficits in turn lead to disorganized responding to the environment and to stimulation seeking to increase the rate of stimuli input (i.e., hyperactivity, impulsivity; Rapport, Alderson, et al., 2008). Increased motor activity associated with stimulation seeking therefore serves to compensate for cortical underarrousal by increased dopamine transmission and to improve cognitive functioning, refresh WM mental representations, and lastly, to function as an escape behavior that is negatively reinforced by environmental stimuli (e.g., inadvertent reinforcement for off-task behavior by a teacher; Rapport et al., 2001; Rapport, Kofler, Alderson, & Raiker, 2008). The functional working memory model is currently the only model of ADHD that provides specific hypotheses for explaining the presence and function of hyperactive behavior associated with ADHD.

The functional working memory model is supported by correlational (i.e., rating scales), experimental, and meta-analytic research. Correlational research employing rating scales has indicated that working memory deficits are present in children with ADHD (e.g., Alloway et al., 2009) and that working memory deficits are related to problematic classroom behaviors such as poor work quality and problem-solving skills (Gathercole et al., 2008).

Inferences formed from previous correlational study findings are limited, however, since a preponderance of existing correlational studies obtained data from EF questionnaires. That is, previous research on EF questionnaires has indicated that they are typically redundant with items from ADHD rating scales and have poor convergent validity with laboratory measures of EF (McAuley, Chen, Goos, Schachar, & Crosbie, 2010; Toplak, Bucciarelli, Jain, & Tannock, 2008).

In contrast, experimental research allows for objective measurement of between-group differences on carefully-controlled, laboratory based EF tasks that have high face and construct validity (Pennington & Ozonoff, 1996; Toplak, West, & Stanovich, 2012). Moderate to large magnitude deficits of WM (PH storage/rehearsal, VS storage/rehearsal and CE) have been identified in children with ADHD and TD children, with effect sizes ranging from medium to large for PH storage/rehearsal (0.55 to 0.87 standard deviation units), large for VS storage/rehearsal (0.89 to 1.09 standard deviation units), and exceptionally large for the CE (1.23 to 3.76 standard deviation units; Alderson et al., 2010; Friedman et al., 2017; Rapport, Alderson, et al., 2008).

Meta-analytic reviews of WM and ADHD are consistent with experimental research and have found moderate to large effect sizes associated with WM deficits between groups of children with ADHD and TD children (Kasper, Alderson, & Hudec, 2012; Martinussen, Hayden, Hogg-Johnson, & Tannock, 2005; Willcutt et al., 2005). Effect size estimates have ranged from 0.47 to 0.69 and 0.74 to 0.85 for PH and VS storage/rehearsal processes, respectively (Kasper et al., 2012; Martinussen et al., 2005; Willcutt et al., 2005). Moderation analyses have identified best-case procedures in methodological and sample characteristics that are expected to yield large effect sizes (Kasper et al., 2012). Moreover, the use of such best-case procedures suggest that 98% of children with ADHD experience WM deficits relative to their TD peers (i.e., 98% of children with ADHD are expected to have WM performance below the mean WM performance of TD children; Kasper, et al., 2012).

Most previous studies of WM and ADHD have examined the role of PH and VS storage/rehearsal processes and the CE, while ignoring the EB. To date, only one published study has investigated the role of the episodic buffer in children with ADHD. Alderson and colleagues (2015) compared performance on three phonological working memory tasks that differed by stimulus presentation modality (auditory, visual, and dual auditory and visual). Potential changes from the auditory to the visual condition were hypothesized to involve processes related to the EB and orthographic to phonological conversion, whereas differences between the visual and dual condition were hypothesized to be the result of EB-related processes beyond those associated with the visual condition. Importantly, the visual condition served as a methodological control such that it provided an intermediary condition between the auditory and dual conditions. That is, including a visual condition precluded the possible argument that performance differences between the two conditions (auditory and dual) were solely due to visual presentation of stimuli. Collectively, findings indicated children with ADHD exhibited the greatest deficit during the auditory presentation condition, and did not benefit from multimodal binding to the same extent as their TD peers (Alderson, Kasper, et al., 2015).

ADHD, Working Memory, and Outcomes

Extant research has further validated the functional working memory model by examining the extent to which WM deficits underlie other EF problems, such as inhibition, impulsivity, and self-control. For example, a study by Alderson and colleagues (2010) examined the directional relationship between WM components (PH storage/rehearsal, VS storage/rehearsal, and CE) and a commonly used metric of behavioral inhibition (Stop Signal Reaction Time; SSRT) among a sample of boys with and without ADHD. Findings from mediation analyses indicated that behavioral inhibition did not account for ADHD-related PH or VS storage/rehearsal deficits, and only partially accounted for the CE deficits observed in the ADHD group. In contrast, group exerted a significant indirect effect on inhibition through the CE, suggesting that behavioral inhibition was downstream of WM processes. A subsequent examination of the directional relationship between WM and performance on a low-density continuous performance test (CPT) yielded a similar pattern of findings (Raiker, Rapport, Kofler, & Sarver, 2012), suggesting the relationship between WM and inhibition is relatively robust across various metrics of inhibition. Even more, findings from a recent experimental study suggest that behavioral inhibition may be subsumed within the WM construct rather than being a discrete entity (Alderson, Patros, et al., 2015).

While the relationship between ADHD-related working memory impairments and inhibition is well studied, emerging findings appear to suggest that other neurocognitive deficits characteristic of the disorder are also downstream of impairments of working memory. For example, findings from Patros and colleagues (2015) suggest a significant indirect effect of VS WM through choice-impulsivity on ratings of overall ADHD, inattention ratings, and hyperactivity/ impulsivity ratings, and the CE has been found to mediate ADHD-related reaction time variability (Kofler et al., 2014). These findings contrast predictions from models of ADHD that suggest delay aversion (Sonuga-Barke, 2005; Sonuga-Barke et al., 2010) and reaction time variability (Castellanos et al., 2005; Tamm et al., 2012) serve as core features/underlying mechanisms of ADHD, rather than behavioral outcomes of a taxed working memory system.

WM impairment has also been found to underlie tertiary symptoms commonly associated with ADHD, such as poor social skills and academic impairment. For example, Kofler et al. (2011) found that CE working memory processes had an indirect effect on social problems through ADHD symptoms. Poor overall WM is related to poor math (Alloway, Gathercole, & Elliott, 2010; Rogers, Hwang, Toplak, Weiss, & Tannock, 2011; Simone, Marks, Bédard, & Halperin, 2017) and reading performance (Alloway et al., 2010; Jacobson et al., 2011; Rogers et al, 2011; Simone et al., 2017) in children and adolescents with ADHD. Not surprisingly, the CE that is involved with manipulation, re-ordering, switching, and dividing attention (Baddeley, 2007) appears to be particularly important to math achievement in affected children (Bull, Espy, & Wiebe, 2008; Friedman et al., 2017).

Working Memory and ADHD-Related Hyperactivity

Extant research has provided overwhelming support for a functional relationship between WM demands and motor activity, in which children with ADHD, relative to typically developing children, exhibit a disproportionate increase in motor activity as working memory demands increase. Porrino et al.'s (1983) seminal study provided the first objective measure of motor activity in boys with and without ADHD. Children wore actigraphs continuously over a seven-day period and their activities (e.g., watching television, outside play, mathematics) were coded using data from self- and teacher-reported daily activities. Findings indicated that boys with ADHD exhibited higher levels of overall activity relative to their TD peers. Notably, children with ADHD, compared to children without ADHD, exhibited higher levels of activity during academic tasks such as reading or mathematics, but there were no significant between-group differences in activity during recreational activities such as recess and physical education. These findings appear to suggest a relationship between task demands and motor activities. Several methodological limitations of the study should be noted, however. Activity level was measured by actigraphs secured to the waist, which does not capture subtle variations in motor activity such as finger tapping or fidgeting (Rapport et al., 2006). Additionally, motor activity was not examined with respect to the presence of on- or off- task behavior.

More recent studies have expanded on this seminal study by employing more advanced methodological designs and statistical approaches. For example, Rapport et al. (2009) objectively measured activity with actigraphs placed on both ankles and non-dominant wrist of boys with ADHD and typically developing boys during three laboratory conditions (a VS WM task, a PH WM task, and a control task hypothesized to place minimal demands on WM). Findings suggested that, compared to their typically developing peers, boys with ADHD demonstrated higher overall activity, and disproportionately greater activity during the VS and PH WM tasks. Notably, exceptionally large effect sizes were identified for between-group differences in activity, ranging from 1.49 (PH storage/rehearsal) to 1.83 (VS storage/rehearsal) standard deviation units. Additional analyses examining the role of WM components indicated that the CE, but not VS or PH storage/rehearsal processes, contributed to increased activity for both groups. Collectively, these findings suggests that variability in CE-WM demands are functionally related to ADHD-related hyperactivity.

Alderson and colleagues (2012) provided further support for the functional relationship between increased cognitive demands and motor activity. Specifically, motor activity (measured by actigraphs on the wrist of the non-dominant hand and two ankles) among boys with ADHD and their typically developing peers was recorded while they completed a stop-signal task, two choice tasks variants, and control conditions. Similar to previous findings, the ADHD group was more active than the TD group for all tasks, and both groups evinced more activity during the experimental tasks, relative to the control conditions. Moreover, for both groups, activity during the stop-signal task (hypothesized to require behavioral inhibition) was not significantly different compared to activity exhibited during the choice tasks (requiring attention but not behavioral inhibition), indicating that increased activity was associated with the CE, and not behavioral inhibition.

Similarly, Patros and colleagues (2017) examined objectively measured motor activity in boys with ADHD and TD boys during VS WM and self-control tasks. Not surprisingly, children with ADHD exhibited greater motor activity relative to TD children, and both groups exhibited greater activity during VS WM and self-control conditions, compared to control conditions. Notably, follow-up regression analyses revealed that VS WM performance predicted more variance in activity across both VS WM and self-control tasks.

Although a growing body of literature provides strong converging evidence that WM demands underlie ADHD-related hyperactivity (Alderson et al., 2012; Patros et al., 2017; Rapport et al., 2009), as evidenced by significant increases in motor activity from control conditions to WM tasks, an alternative explanation for such findings could be that any tasks that requires sustained attention may be sufficient to elicit increases in motor activity. Hudec et al.'s (2015) subsequent study therefore aimed to determine the extent to which varying EF and non-EF task demands were related to variability in motor activity. Boys with ADHD and TD boys completed tasks requiring high (two *n*-back tasks), moderate (choice-reaction time task; CRT), low (simple reaction time task; SRT), and minimal (control condition) levels of cognitive resources while wearing actigraphs on their ankles. Although the interaction between group and condition was not significant, consistent with previous findings, there were significant main effects for both group (ADHD more active than TD) and condition (more activity during experimental tasks compared to the control conditions). Collectively, the SRT and CRT conditions elicited increased motor activity, relative to activity observed during the control condition, suggesting that relatively small cognitive demands were sufficient to elicit significant increases in motor activity. More importantly, children exhibited the greatest motor activity during the *n*-back working memory conditions, consistent with predictions from the WM model of ADHD.

In contrast to previous research that has demonstrated between-group differences in motor activity across broad WM conditions, a recent study completed a more focused examination of objectively measured motor activity (i.e., actigraphy) in children with ADHD by examining covariance in motor activity and trial-by-trial performance on a flanker task (Hartanto et al., 2016). Collectively, children with ADHD exhibited greater motor activity than did the TD children, but only for correct trials. Moreover, there was a significant interaction between group and performance, suggesting greater activity was associated with better performance for children with ADHD.

Lastly, a recent meta-analytic review of objectively measured activity in children, adolescents, and adults with ADHD and their typically developing peers identified several moderating variables (other than group membership) that contributed to between-differences in activity (Kofler et al., 2016). Findings from the review suggest that between-group differences in objectively- measured activity are highest when activity is measured under conditions requiring high WM demands and grouping is based on multi-informant, multi-method diagnoses. Therefore, rigorous diagnostic grouping and the use of tasks that necessitate the *working* component of working memory (Baddeley, 2007) are essential to obtain accurate information about differences in motor activity between children with ADHD and TD children.

Collectively, findings from experimental (Alderson et al., 2012; Hartanto et al., 2016; Hudec et al., 2015; Patros et al., 2017; Porrino et al., 1983; Rapport et al., 2009) and meta-analytic (Kofler et al., 2016) research have provided exceptionally strong evidence for a functional relationship between WM demands and motor activity. However, previous research examining ADHD, activity, and working memory have exclusively focused on the role of the CE, PH storage/rehearsal, and VS storage/rehearsal, without attending to the role of EB processes. Further experimental examination of the EB may have implications for models of ADHD, teaching strategies, and psychological treatment.

Current Study

The current study is the first to examine EB binding and motor activity in an ADHD sample. Previous research examining WM and ADHD have exclusively focused on the role of the CE and PH and VS storage/rehearsal processes, and ignored the potential role of EB processes. This gap in the literature may be due to the EB's relatively recent status within Baddeley's model, having only been added in 2000. Nonetheless, investigation of the role of the EB vis-à-vis ADHD-related hyperactivity is critical, given that the sole study investigating the EB in a sample of children with ADHD yielded performance differences related to stimulus presentation modality and provided evidence of differential EB-related processes in children with ADHD. Identifying the nature of differences in EB processes in children with ADHD may lead to the implementation of alternative teaching strategies (e.g., adjusting the type and number of modalities used during instruction) that may help alleviate the significant academic achievement difficulties that affect most children with ADHD. Further, clarifying the relationship between motor activity, the EB, and ADHD will further understanding of causal mechanisms of ADHD and have implications for optimal psychological treatment (e.g., presentation of materials, psychoeducation to help children with ADHD and their caregivers to identify appropriate compensatory strategies). Previous research has revealed significant differences in CE functioning in children with ADHD (Alderson et al., 2010; Rapport, Alderson, et al., 2008), but these estimates have been calculated without consideration of the role of EB processes and therefore may have overestimated the role of the CE (Alderson, Kasper, et al., 2015). Further investigation of the EB would thus provide a more accurate understanding of the extent to which children with ADHD experience deficits across WM components and could add to a growing body of literature examining the role of the CE across psychological disorders (Alderson, Patros, et al., 2015; Huang-Pollock, Shapiro, Galloway-Long, & Weigard, 2017; Miyake et al., 2000). Accordingly, the current study will examine the relationship between group membership and type of working memory task determine the effect of EB-related processes on WM performance and motor activity. The EB will then be statistically estimated so that motor activity uniquely related to EB processes can be identified.

Hypotheses

Hypothesis I (Performance Across Working Memory Conditions)

A significant interaction effect between group (ADHD, TD) and WM condition (PHA, PHV, PHD, and VS) on performance is expected based on previous research identifying a significant group by modality interaction (Alderson, Kasper, et al., 2015). Previous research has also identified medium to large effect sizes for between-group effects in WM performance varying by condition (Rapport et al., 2008; Kasper et al., 2012). Within the ADHD group, performance is expected to be best during the three PH conditions relative to the VS condition (based on previous findings demonstrating improved performance during a PHV task compared to a VS task; Rapport, Alderson, et al., 2008). Further, PHD and PHV performance is not expected to be significantly different in children with ADHD, and performance during PHD and PHV will be better than during PHA (Alderson, Kasper, et al., 2015). TD children are expected to evince their best performance during PHD compared to all other WM conditions, based on findings by Alderson and colleagues (2015). No significant differences are expected in performance on PHV and PHA, and TD children are hypothesized to have their lowest performance on the VS task. Between-group differences are expected across all conditions such that TD children will have better performance (a higher number of average stimuli correct) than will children with ADHD (based on previous research from Rapport, Alderson, et al., 2008; Alderson et al., 2010). Between-group differences are expected to be larger for the VS task than for the three PH tasks, based on previous research (Rapport, Alderson, et al., 2008).

Hypothesis II (Motor Activity Across Conditions)

A significant interaction effect between group (ADHD, TD) and condition (C1, C2, PHA, PHV, PHD, and VS) on activity is expected based on previous research identifying medium to large effect sizes for between-group differences in activity across WM and control conditions (Hudec et al., 2015; Rapport et al., 2009). Within the ADHD group, activity during the experimental WM tasks is expected to be significantly higher than during the control conditions, and activity during the three PH conditions is expected to be higher than during the VS condition, based on previous research findings with the same pattern of results (Rapport et al., 2009). Activity during the PHA condition is expected to be significantly higher than during the PHD and PHV conditions, which are not expected to significantly differ in activity. These findings are expected based on previous research on WM performance in children with ADHD (Alderson, Kasper, et al., 2015) and predictions from the functional working memory model (i.e., motor activity increases as a function of WM demand; Rapport, Alderson et al., 2008). For the TD group, activity is expected to be significantly higher during the PHV and PHA conditions relative to the PHD and VS conditions. (Alderson, Kasper et al., 2015; Rapport, Alderson et al., 2008). Activity during PHV and PHA is not expected to be significantly different for the TD group. Children with ADHD are expected to have greater activity relative to children without the disorder, based on previous findings (Hudec et al., 2015; Patros et al., 2017; Rapport et al., 2009). Between-group differences in activity during the experimental tasks (PHA, PHV, PHD, VS) are expected to be significantly higher than observed differences in activity during the control conditions, and between-group differences for PHA are expected to be larger than for PHV and PHD, based on previous research by Alderson, Kasper, et al. (2015) and predictions of the functional working memory model (Alderson et al., 2015; Rapport, Alderson, et al., 2008).

Hypothesis III (Episodic Buffer Contribution to Motor Activity)

Children with ADHD are expected to have higher levels of EB-associated activity than TD children, based on previous research documenting significant between-group differences in activity associated with all previously-studied components of WM (i.e., the CE, PH storage/rehearsal, and VS storage/rehearsal processes; Rapport et al., 2009; Hudec et al., 2015). Recent research by Alderson and colleagues (2015), however, suggests that previous research may have overestimate the CE's contribution to activity levels by inadvertently including activity related to the EB within the estimate of CE. This inadvertent inclusion of EB-related processes also lends credence to the hypothesis of significant between-group differences in EB-associated activity.

Proposed Method

Participants

The proposed study will include typically developing (TD) children and children with ADHD aged 8-12 years, recruited by the Center for Research of Attention and Behavior (CRAB). Participants will be recruited from the community via fliers in local businesses, word of mouth, and through the Psychological Services Center (PSC), a university-based mental health clinic. Parental consent and child assent will be obtained prior to participation, and the Institutional Review Board (IRB) will approve the study before data is collected. Child participants will be grouped as TD or as ADHD based on the results of an evaluation consisting of well-established, reliable, and valid behavior rating scales completed by parents and teachers, cognitive and achievement testing, and clinical interviews. In exchange for participation, parents of participants will be provided with comprehensive psychoeducational reports from the child's evaluation.

Group Assignment

To be included in the ADHD group, children will meet the following criteria: (1) a diagnosis by the Center for Research of Attention and Behavior's directing clinical psychologist based on DSM-5 (APA, 2013) criteria for an ADHD diagnosis, supplemented by information provided by parents on the K-SADS-PL semi-structured clinical interview, (2) parent ratings at least 1.5 standard deviations (i.e, within the clinical range) greater than the mean on the DSM-oriented ADHD scales of the Conners-3P or at least 2 standard deviations greater than the mean on the ADHD scales of the CBCL, and (3) teacher ratings at least 1.5 standard deviations (i.e., within the clinical range) greater than the mean on the DSM-oriented ADHD scales of the Conners-3T or at least 2 standard deviations greater than the mean on the ADHD scales of the TRF. Due to the high level of comorbidity with ADHD diagnoses (Wilens et al., 2002), children with comorbid diagnoses will not be excluded from the ADHD group.

To be included in the TD group, children will meet the following criteria: (1) no diagnosis by the Center for Research of Attention and Behavior's directing clinical psychologist based on DSM-5 (APA, 2013) criteria, evidenced by information provided by parents on the K-SADS-PL semi-structured clinical interview and the standardized behavior rating scales, and (2) normal developmental history based on information provided by the parent during a psychosocial interview.

All children will be required to discontinue the use of psychostimulant medication 24 hours prior to research sessions. Children presenting with (1) gross neurological, sensory, or motor impairment, (2) history of seizure disorder, (3) psychosis, and/or a (4) a *Wechsler Intelligence Scale for Children-Fifth Edition* (WISC-V) Full Scale IQ (FSIQ) score less than 80 will be excluded from the study. Neurological impairment (e.g., traumatic brain injury) or intellectual disability would likely confound results (i.e., it would be unclear if group differences in working memory performance or activity were due to a difference between children with ADHD and TD children or if the difference was attributable to neurobiological impairment or intellectual disability). Similarly, children with motor impairments will be excluded because increased or decreased motor levels could confound results (it would be unclear if group differences were the result of a true ADHD-TD between-group difference or if they were an artifact of motor impairment). Children with sensory impairment will be excluded from the study because they may be unable to see or hear stimuli in order to complete the working memory tasks. Due to the rapid visual nature of some of the experimental tasks, children with seizure disorder may be at risk for having a seizure, and will therefore also be excluded from the study.

Measures

Psychosocial and clinical interviews. A psychosocial interview will be administered to parents of participants to assess pregnancy history (pre, peri, post), developmental history, medical history, educational history, family history, and current social functioning. Information from this interview will be integrated with other interview and rating scale data in order to best determine the presence or absence of any diagnosis(es) in accordance with DSM-5 diagnostic criteria. Information gleaned from this interview will also be incorporated into the comprehensive psychoeducational report provided to parents of participants.

The *Kiddie Schedule for Affective Disorders and Schizophrenia Present and Lifetime Version (K-SADS-PL)* will be used to assess onset, course, frequency, severity, and duration of symptoms linked to various affective, psychotic, anxiety, behavioral, and substance abuse disorders based on DSM-5 diagnostic criteria. This semi-structured clinical interview has strong psychometric properties. Test-retest reliability for current diagnoses ranges from acceptable to excellent (k = .63 to 1.00; Kaufman et al., 1997). The K-SADS-PL has good overall convergent and discriminant validity with other measures of behavioral and psychiatric disorders (e.g., Early Childhood Inventory-4 and Child Behavior Checklist; Birmaher, et al., 2009; Pelham, Fabiano, & Massetti, 2005).

Behavior rating scales. To assess child functioning across situations, and consistent with the gold-standard for ADHD assessment (Gualtieri & Johnson, 2005; Weiss, 2010), rating scales from multiple reporters (parent and teacher) will be used. Information from these broad and narrow band measures will inform diagnosis.

***Child Behavior Checklist and Teacher Report Form*.** The *Child Behavior Checklist* (CBCL) and *Teacher's Report Form* (TRF) provide age-normed ratings of children's emotional and behavioral functioning (Achenbach, & Rescorla, 2001). The CBCL and TRF provide two broadband dimensions (internalizing and externalizing) and 8 narrow-band clinical domain scores (e.g., rule-breaking behavior, aggressive behavior, anxious/depressed, withdrawn/depressed, somatic complaints), as well as clinical DSM-oriented scales that correlate with symptoms of disorders found in the *Diagnostic and Statistical Manual for Mental Disorders, 4th edition* (DSM-IV). Additionally, the

Attention Problems syndrome and DSM-oriented scales on the TRF are further subdivided into Inattention and Hyperactivity-Impulsivity subscales. The test-retest reliability ranges from good to excellent across the CBCL (α = .82-.94) subscales, and ranges from adequate to excellent across TRF subscales (α = .60-.96; Achenbach & Rescorla, 2001). Internal consistency ranges from fair to excellent across the CBCL (α = .78-.97) and TRF (α = .72-.97; Achenbach & Rescorla, 2001) subscales. In previous studies, the CBCL has distinguished between ADHD subtypes (Ostrander, Weinfurt, Yarnold, & August, 1998) and has strong construct validity (Biederman et al., 1995).

Conners 3 Parent and Teacher Rating Scales. The Conners 3- Parent (C3-P) and Conners 3- Teacher (C3-T) are narrow band measures designed to assess externalizing behaviors in children aged 6-18 years. The measures provide six content scales and four DSM-5 oriented scales. The Conners 3 also provides validity scales that indicate whether the responses suggest a positive impression, negative impression, or inconsistency index. An ADHD Index Score provides a measure of how strongly a classification of ADHD is indicated, and 3 Global Index Scores summarize measures of emotional and behavioral ratings. The internal consistency of the C3-P and the C3-T ranges from very good to excellent (α = .77-.97), and both measures have high test-retest reliability (r = .71-.98) and good convergent validity (Conners, 2008).

Children's Depression Inventory. Children will complete the *Children's Depression Inventory* (CDI; Kovacs, 2003), a 27-item self-report measure, to assess for depression-related symptoms. The CDI is appropriate for use in children aged 7 to 17 and has adequate internal consistency for each of its five scales (negative mood, interpersonal problems, ineffectiveness, anhedonia, and negative self-esteem; α = .59-.68; Kovacs, 2003). Further, extant research on the CDI has demonstrated strong discriminative and concurrent validity (Kovacs, 2003).

Revised Children's Manifest Anxiety Scale-2. Children will complete the *Revised Children's Manifest Anxiety Scale-II* (RCMAS-2; Reynolds, & Richmond, 2008) to assess for anxiety-related symptoms. The RCMAS-2 is a 49-item self-report measure for children aged 6 to 19, and measures three areas of functioning: physiological anxiety, worry, and social anxiety. The measure also includes two validity scales, one for social desirability (defensiveness), and another to detect biased responding and validity (inconsistent responding index). The RCMAS-2 has outstanding internal consistency for the Total Anxiety scale ($\alpha = .92$), and good to excellent internal inconsistency for the subscales ($\alpha = .75$-$.86$; Reynolds & Richmond, 2008). One-week test-retest reliability ranges from adequate to good ($\alpha = .64$-$.76$; Reynolds & Richmond, 2008) across the Total Anxiety scale and the subscales. The RCMAS-2 evinces good construct validity (Reynolds & Richmond, 2008)

Intellectual and Academic Functioning

Wechsler Intelligence Scale for Children-Fifth Edition. Children will complete all subtests of the *Wechsler Intelligence Scale for Children-Fifth Edition* (WISC-V; Wechsler, 2014) to assess current intellectual functioning. The WISC-V has outstanding psychometric properties including high internal consistency, test-retest reliability, content validity, criterion validity, and construct validity (Wechsler, 2014). The WISC-V will be used to determine study inclusion (FSIQ > 80).

Kaufman Test of Educational Achievement – Third Edition. Children will complete the *Kaufman Test of Educational Achievement – Third Edition* (KTEA-3) to measure current academic achievement and to confirm that children will be able to understand the tasks administered during the research sessions. The KTEA-3 evinces strong psychometric properties, with composite score reliability ranging from good to excellent (α = .92-.99), with the exception of Oral Fluency (α = .70-.74; Kaufman & Kaufman, 2014). The KTEA-3 has strong content and construct validity (Kaufman & Kaufman, 2014).

Experimental Tasks

Phonological (PH) working memory task. A PH working memory task (Rapport, Alderson, et al. (2008), will be used to measure children's phonological working memory as described by Baddeley's (2007) model. The PH working memory task requires participants to re-order a jumbled series of single digit numbers and one letter, similar to the Letter-Number Sequencing subtest of the WISC-V (Weschler, 2014). Children will be instructed to rearrange and say the numbers in order from least to greatest and say the letter last (see Figure 1). Participants will use a touch-screen computer (37 x 30 cm monitor screen) to complete the task, which was programmed using SuperLab Pro 4.0 (Cedrus, San Pedro, CA) software.

The PH working memory task will be presented via three modality conditions (auditory, visual, and dual), each with four set size blocks consisting of 24 trials each. Stimuli will be presented in counterbalanced order (determined using a Latin Square design) to control for possible order effects. For the phonological auditory (PHA) condition, stimuli will be presented through the computer's speakers. In the visual (PHV) condition, stimuli will successively appear on the computer screen. The stimuli will measure 5.1cm high and all letters will be capitalized in bold, size 200, Times New

Roman font. In the dual (PHD) condition, stimuli will be both simultaneously presented verbally and visually.

The letter will never be presented first or last within each trial in order to decrease the likelihood of primacy or recency effects. Additionally, no stimulus will be presented twice in the same trial. Each stimulus will be presented for 800 ms, followed by a 200 ms inter-stimulus interval. Following the presentation of the final stimulus within a trial, an auditory “click” will sound and a green traffic light will appear on the screen to prompt the children to verbally respond. Following their response, children will touch the screen to advance to the next trial, upon which another auditory “click” will sound to signify the beginning of a trial. The next trial will automatically advance if children do not touch the screen within a pre-specified amount of time (10,000 ms per stimulus to respond, i.e., 40,000 ms for set size 4). Two coders situated behind a one-way mirror will independently record verbal responses. Coders’ responses will be checked for inter-rater agreement, and any discrepancies between coders will be resolved by checking video and audio recordings of the task.

Two practice blocks of five trials will be administered prior to task administration for set sizes 3 and set size 4, 5, or 6. The practice block for set size 3 will consist of three stimuli, and the practice block for set size 4, 5, or 6 will consist of four stimuli. For set size 3, the letter will always appear second in each series. In set sizes 4 through 6, the letter will be presented between the first and last stimuli, in a counterbalanced order (determined using a Latin Square design). To ensure that children understand the instructions, an 80% or higher success rate will be required during practice blocks before beginning the experimental trials.

Visuospatial (VS) working memory task. Visuospatial working memory will be assessed via a computerized task from Rapport, Alderson, et al. (2008) that was programmed using SuperLab Pro 4.0 (Cedrus, San Pedro, CA). Colored dots (all black except for one red) will sequentially appear within boxes on an offset grid on a touch screen computer, and children will be instructed to touch the boxes in the same order that the black dots appeared, and to touch the box that the red dot appeared in last (see Figure 2). The offset grid will consist of three columns containing three boxes each (each measuring 2.85 x 2.85 cm). The grid will be offset from a typical 3 x 3 grid to reduce the likelihood that children will utilize PH encoding by assigning mental placeholders to each box (e.g., assigning values to each box like a telephone keypad). The red dot will never appear first or last in order to reduce the likelihood of recency or primacy effects. That is, for set size 3, the red dot will always appear second in the stimuli presentation, and in set sizes 4 through 6, the red dot will be counterbalanced between the first and last stimuli.

The VS task will consist of four blocks of varying set sizes (3, 4, 5, and 6) that correspond to the number of stimuli, and each block will consist of 24 trials. Blocks will be presented in counter-balanced order (determined using a Latin Square design) to control for order effects. Each dot, measuring 2.22 cm in diameter, will appear sequentially for 800 ms with a 200 ms inter-stimulus interval. After each trial of stimuli presentation, a blank grid will appear to cue children to respond (see Figure 3). Children will be allowed a maximum of 10,000 ms to respond to each stimulus (i.e., 10,000 ms for each dot). Following the children's entire response for a trial, or if the response time is exceeded, there will be a 1,000 ms inter-trial interval. Afterward, the computer will sound an auditory "click" to indicate a new trial will be presented after an additional 1,000 ms.

Two practice blocks of five trials will be administered prior to task administration for set size 3 and set size 4, 5, or 6. The practice block for set size 3 will consist of three stimuli, and the practice blocks for set size 4, 5, or 6 will consist of four stimuli. To ensure that children understand the instructions, an 80% or higher success rate will be required during practice blocks before beginning the experimental trials.

Control condition. At the beginning and end of each research session, children will spend five minutes using the Microsoft Paint ® program to draw or paint anything of their choice. This task will serve as a methodological control as it requires children to engage the computer, but is expected to place minimal working memory demands on children compared to the PH tasks (Hudec et al., 2015). The use of two control conditions will also allow for the examination of potential fatigue effects on motor activity.

Motor activity. *MicroMini Motionlogger ® Actigraphs* will be used to objectively measure motor activity. Three actigraphs will be attached with a Velcro ® band to each participant's non-dominant wrist and above each ankle. Actigraphs will be placed on participants' non-dominant hand so that measured motor activity is not confounded with task demands, e.g., touching the computer screen. Children will be told that "special watches" are being used to help communicate with the computer. Actigraphs will be set to the proportional integrating measure, low (PIMlow), in order to measure the intensity of gross motor activity. The Observer XT version 8.0 (Noldus Information Technology, 2008) observation software will be used to record time stamps for the start and stop of each task. Data from each of the actigraphs will be uploaded into the Action4 (Ambulatory Monitoring Inc., 2010) computer program and matched to the recorded time stamps. Motor activity for each task will be summed across the three sites (non-dominant hand, left ankle, and right ankle) to create a Total Extremity Score (TES) for each condition (PHA, PHV, PHD, VS, and control).

Procedure

After all rating scales are completed, children and parents will participate in two clinical sessions to assess intellectual functioning, academic achievement, developmental history, and any clinical symptomatology. The clinical sessions will be scheduled for weekday mornings in order to obtain the best estimate of children's performance that is minimally affected by potential fatigue associated with testing later in the day. After obtaining informed consent and child assent in the first clinical session, one graduate student of the Center for Research of Attention and Behavior (CRAB) associate will complete the psychosocial interview with the parents, while a second graduate student associate will administer the WISC-V to the child. Parents will also complete a demographic information form with information on child ethnicity, parental education, and occupational status. In the second session, one CRAB associate will complete the clinical interview with the parents, while a second associate will administer the KTEA-3 to the child.

Following the clinical testing sessions of the study, children will participate in approximately three research sessions scheduled for Saturday mornings or afternoons. Each research session will last for approximately three hours. The working memory tasks will be completed as a part of a larger battery of experimental tasks and will be administered in counterbalanced order across research sessions. Breaks will be taken after every two to four tasks, or as needed, in order to reduce cognitive fatigue and possible frustration. Children will complete the CDI during the first research session and the

RCMAS-2 during the second. After completion of the clinical and research sessions, parents will attend a feedback session wherein the comprehensive psychoeducational report and discussion of findings will be provided to parents.

Proposed Analyses

Outliers

Independent and dependent variables will be independently screened by group (ADHD, TD) for univariate outliers as part of the preliminary analyses. Outliers will be defined as values at least 3.29 standard deviations greater than or less than the mean for each group (i.e., $p < .001$; Tabachnick & Fidell, 2001). Values greater or less than 3.29 standard deviations from the mean will be replaced with a value equal to ±3.29 standard deviations from the mean.

Preliminary Analyses

Demographic data (age, SES, FSIQ, and ethnicity) will be examined for each group using independent samples *t*-tests (age, FSIQ, SES) and Pearson's chi squared tests (ethnicity) to determine the need for covariate analyses. Between-group differences for the rating scale measures (CBCL, TRF, C3-P, C3-T, CDI, and RCMAS-2) will be tested using independent samples *t*-tests.

A priori power analyses

Performance. A priori power analyses were conducted using G* Power software (v 3.0.10; Faul, Erdfelder, Lang, & Buchner, 2007) to determine the number of participants required to detect an interaction, between-group differences, and within-group differences in WM performance in a repeated measures ANOVA. An effect size of $d = 0.87$ was chosen based on the average magnitude of previously reported effect sizes for PH and VS storage/rehearsal processes (Alderson et al., 2010; Rapport, Alderson et al., 2008[4]). Based on Cohen's (1992) conventions, power was set at 0.80 and an alpha level of 0.05 was chosen. Based on these values and the inclusion of two groups with four conditions (PHA, PHV, PHD, and VS), 30 total participants (15 per group) are needed to detect between-group differences, and 10 total participants (5 per group) are needed to detect within-group differences and interaction effects. Accordingly, data for at least 15 participants per group will be collected.

Activity. A priori power analyses were conducted using G* Power software (v 3.0.10; Faul et al., 2007) to determine the number of participants required to detect an interaction, between-group differences, and within-group differences in motor activity in a repeated measures ANOVA. A Cohen's *d* effect size of 1.74 was chosen based on the average magnitude of effect sizes reported in studies examining motor activity and WM in children with ADHD and TD children (Rapport et al., 2009[5]). Based on an effect size of $d = 1.74$, power = .80 (as recommended by Cohen, 1992), $\alpha = .05$, two groups, and six conditions (PHA, PHV, PHD, VS, C1, and C2), 10 total participants (5 per group) are needed to detect between-group differences, and four total participants (2 per group) are needed to detect within-group differences and interaction effects. These results suggest that the planned sample size of at least 30 (15 participants per group) will be more than sufficient to reliably detect between, within, and interaction effects.

Tier I: Performance Across Working Memory Conditions

Average stimuli correct per trial will be computed for each set size (3, 4, 5, and 6) of each working memory condition (PHA, PHV, PHD, VS) and then averaged across set sizes to create four total working memory performance variables (one for each

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[4] Hedge's *g* effect sizes were reported in Rapport, Alderson, et al. (2008) and were converted to Cohen's *d*.
[5] Hedge's *g* effect sizes were reported in Rapport et al. (2009) and were converted to Cohen's *d*.

condition). A subsequent 2 x 4 mixed model ANOVA will examine the effect of group on working memory condition. If a significant interaction is present, two post hoc repeated measures ANOVAs (one for each group) will be performed to detect any performance differences across conditions. LSD post hoc comparisons will be used to identify differences within condition if either repeated measures ANVOA reveals significant within group effect(s). Post hoc t-tests will examine between-group performance differences at each working memory condition.

Tier II: Motor Activity Across Conditions

A composite total extremity score (TES) will be computed for activity level by summing the TES from each condition across set sizes (PH, VS; 3, 4, 5, and 6) or averaging across research day (control condition). A 2 x 6 mixed model ANOVA will examine the effect of condition (PHA, PHV, PHD, VS, C1, C2) on activity level, with group serving as the between-subjects factor and condition serving as the within-subjects factor. If a significant interaction is present, two post hoc repeated measures ANOVAs (one for each group) will be used to examine the effect of condition on motor activity. LSD post hoc comparisons will probe for differences within condition if either repeated measures ANOVA reveals significant within group effect(s). Post hoc t-tests will examine between-group differences in activity at each working memory condition.

Tier III: Episodic Buffer Contribution to Activity (Working Memory Component Analysis)

A series of regressions will be utilized to compute a variable representing the episodic buffer component of working memory (similar to procedures outlined in Alderson, Hudec, Patros, & Kasper, 2013; Rapport et al., 2009). PHA working memory performance data will be regressed onto VS performance data for each set size. The four resultant residual scores will represent VS storage/rehearsal processes at each set size and the four resultant predicted scores will represent CE processes at each set size. In a similar process, VS working memory performance data will be regressed onto PHA performance data. The resultant residual scores will represent PHA storage/rehearsal, while the predicted scores will represent CE processes. The four VS storage/rehearsal variables will be averaged together to create one VS storage/rehearsal variable, the four PH storage/rehearsal variables will be averaged together to create one PH storage/rehearsal variable, and the eight predicted scores representing CE processes will then be averaged together to create one CE variable.

Next, the PHA storage/rehearsal, VS storage/rehearsal, and CE variables will be simultaneously regressed onto PHD working memory performance. The resultant residual score will represent the EB (i.e., WM variability not related to CE, PH storage/rehearsal, or VS storage/rehearsal processes). Lastly, the EB variable will be regressed onto the overall TES composite score (the sum of each TES composite score for each condition) and the resultant predicted score will represent activity associated with EB processes. Potential between-group differences in EB-related activity will be examined subsequently be examined with a simple *t*-test. A visual schematic of the regression approach is illustrated in Figure 4.

References

Abikoff, H. B., Jensen, P. S., Arnold, L. L. E., Hoza, B., Hechtman, L., Pollack, S., . . . Wigal, T. (2002). Observed classroom behavior of children with ADHD: Relationship to gender and comorbidity. *Journal of Abnormal Child Psychology, 30*(4), 349-359. doi:10.1023/A:1015713807297

Achenbach, T. M., & Rescorla, L. A. (2001). *Manual for the ASEBA school-age forms and profiles*. Burlington, VT: University of Vermont, Research Center for Children, Youth, and Families.

Alderson, R. M., Hudec, K. L., Patros, C. H. G., & Kasper, L. J. (2013). Working memory deficits in adults with attention-deficit/hyperactivity disorder (ADHD): An examination of central executive and storage/rehearsal processes. *Journal of Abnormal Psychology, 122*(2), 532-541. doi:10.1037/a0031742

Alderson, R. M., Kasper, L. J., Hudec, K. L., & Patros, C. H. G. (2013). Attention-deficit/hyperactivity disorder (ADHD) and working memory in adults: A meta-analytic review. *Neuropsychology, 27*(3), 287-302. doi:10.1037/a0032371

Alderson, R. M., Kasper, L. J., Patros, C. H. G., Hudec, K. L., Tarle, S. J., & Lea, S. E. (2015). Working memory deficits in boys with attention deficit/hyperactivity disorder (ADHD): An examination of orthographic coding and episodic buffer processes. *Child Neuropsychology, 21*(4), 509-530. doi:10.1080/09297049.2014.917618

Alderson, R. M., Patros, C. H. G., Tarle, S. J., Hudec, K. L., Kasper, L. J., & Lea, S. E. (2015). Working memory and behavioral inhibition in boys with ADHD: An experimental examination of competing models. *Child Neuropsychology*, 1-18. doi:10.1080/09297049.2015.1105207

Alderson, R. M., Rapport, M. D., Hudec, K. L., Sarver, D. E., & Kofler, M. J. (2010). Competing core processes in attention-deficit/hyperactivity disorder (ADHD): Do working memory deficiencies underlie behavioral inhibition deficits? *Journal of Abnormal Child Psychology, 38*(4), 497-507. doi:10.1007/s10802-010-9387-0

Alderson, R. M., Rapport, M. D., Kasper, L. J., Sarver, D. E., & Kofler, M. J. (2012). Hyperactivity in boys with attention deficit/hyperactivity disorder (ADHD): The association between deficient behavioral inhibition, attentional processes, and objectively measured activity. *Child Neuropsychology, 18*(5), 487-505. doi:10.1080/09297049.2011.631905

Allen, R. J., Hitch, G. J., Mate, J., & Baddeley, A. D. (2012). Feature binding and attention in working memory: A resolution of previous contradictory findings. *The Quarterly Journal of Experimental Psychology, 65*(12), 2369-2383. doi:10.1080/17470218.2012.687384

Alloway, T. P., Gathercole, S. E., & Elliott, J. (2010). Examining the link between working memory behaviour and academic attainment in children with ADHD. *Developmental Medicine & Child Neurology, 52*(7), 632-636. doi:10.1111/j.1469-8749.2009.03603.x

Alloway, T. P., Gathercole, S. E., Holmes, J., Place, M., Elliott, J. G., & Hilton, K. (2009). The diagnostic utility of behavioral checklists in identifying children with ADHD and children with working memory deficits. *Child Psychiatry and Human Development, 40*(3), 353-366. doi:10.1007/s10578-009-0131-3

Alloway, T. P., Gathercole, S. E., & Pickering, S. J. (2006). Verbal and visuospatial short-term and working memory in children: Are they separable? *Child*

Development, 77(6), 1698-1716. doi:10.1111/j.1467-8624.2006.00968.x

Alloway, T. P., Gathercole, S. E., Willis, C., & Adams, A. M. (2004). A structural analysis of working memory and related cognitive skills in young children. *Journal of Experimental Child Psychology, 87*(2), 85-106. doi:10.1016/j.jecp.2003.10.002

Ambulatory Monitoring Incorporated. (2010). *The micromini motionlogger actigraph and family of single sensor recorders* [User's manual to accompany Act Millenium version 3.31.0.0 and higher (Revision 3.1)]: Ardsley, NY: Author.

Antrop, I., Buysse, A., Roeyers, H., & Van Oost, P. (2005). Activity in children with ADHD during waiting situations in the classroom: A pilot study. *British Journal of Educational Psychology, 75*(1), 51-69. doi:10.1348/000709905X36100

Arnett, A. B., Pennington, B. F., Willcutt, E. G., DeFries, J. C., & Olson, R. K. (2015). Sex differences in ADHD symptom severity. *Journal of Child Psychology and Psychiatry, 56*(6), 632-639. doi:10.1111/jcpp.12337

American Psychiatric Association. (1980). *Diagnostic and statistical manual of mental disorders* (3rd ed). Washington, DC: Author.

American Psychiatric Association. (1987). *Diagnostic and statistical manual of mental disorders* (3rd ed, revised). Washington, DC: Author.

American Psychiatric Association. (2000). *Diagnostic and statistical manual of mental disorders* (4th ed., text revision). Washington, DC: Author.

American Psychiatric Association. (2013). *Diagnostic and statistical manual of mental disorders* (5th ed.). Washington, DC: Author.

Babinski, L. M., Hartsough, C. S., & Lambert, N. M. (1999). Childhood conduct problems, hyperactivity-impulsivity, and inattention as predictors of adult criminal activity. *Journal of Child Psychology and Psychiatry, 40*(3), 347-355. doi:10.1111/1469-7610.00452

Baddeley, A. (2000). The episodic buffer: a new component of working memory? *Trends in Cognitive Sciences, 4*(11), 417-423. doi:10.1016/S1364-6613(00)01538-2

Baddeley, A. (2007). *Working memory, thought, and action*: Oxford University Press, New York, NY.

Baddeley, A. (2012). Working memory: Theories, models, and controversies. *Annual Review of Psychology, 63*(1), 1-29. doi:10.1146/annurev-psych-120710-100422

Baddeley, A., Allen, R. J., & Hitch, G. J. (2010). Investigating the episodic buffer. *Psychologica Belgica, 50*(3-4), 223-243. doi:10.5334/pb-50-3-4-223

Baddeley, A., & Wilson, B. A. (2002). Prose recall and amnesia: Implications for the structure of working memory. *Neuropsychologia, 40*(10), 1737-1743. doi: 10.1016/S0028-3932(01)00146-4

Baddeley, A. D., Hitch, G. J., & Allen, R. J. (2009). Working memory and binding in sentence recall. *Journal of Memory and Language, 61*(3), 438-456. doi:10.1016/j.jml.2009.05.004

Barkley, R. A. (1997). Behavioral inhibition, sustained attention, and executive functions: Constructing a unifying theory of ADHD. *Psychological Bulletin, 121*(1), 65-94. doi:10.1037/0033-2909.121.1.65

Barkley, R. A. (2014a). Educational, occupational, dating and marital, and financial impairments in adults with ADHD. In R. A. Barkley & R. A. Barkley (Eds.), *Attention-deficit hyperactivity disorder: A handbook for diagnosis and treatment.*

(pp. 3-50). New York, NY, US: Guilford Press.

Barkley, R. A. (2014b). History of ADHD. In R. A. Barkley & R. A. Barkley (Eds.), *Attention-deficit hyperactivity disorder: A handbook for diagnosis and treatment.* (pp. 3-50). New York, NY, US: Guilford Press.

Barkley, R. A., Grodzinsky, G., & DuPaul, G. J. (1992). Frontal lobe functions in attention deficit disorder with and without hyperactivity: A review and research report. *Journal of Abnormal Child Psychology, 20*(2), 163-188. doi:10.1007/BF00916547

Barkley, R. A., Murphy, K. R., & Fischer, M. (2008). *ADHD in adults: What the science tells us*. New York: Guilford Press.

Barkley, R. A., & Peters, H. (2012). The Earliest Reference to ADHD in the Medical Literature? Melchior Adam Weikard's Description in 1775 of "Attention Deficit" (Mangel der Aufmerksamkeit, Attentio Volubilis). *Journal of Attention Disorders, 16*(8), 623-630. doi:10.1177/1087054711432309

Barkley, R. A., & Ullman, D. G. (1975). A comparison of objective measures of activity and distractibility in hyperactive and nonhyperactive children. *Journal of Abnormal Child Psychology, 3*(3), 231-244. doi:10.1007/BF00916753

Bauermeister, J. J., Matos, M., Reina, G., Salas, C. C., Martínez, J. V., Cumba, E., & Barkley, R. A. (2005). Comparison of the DSM-IV combined and inattentive types of ADHD in a school-based sample of Latino/Hispanic children. *Journal of Child Psychology and Psychiatry, 46*(2), 166-179. doi:10.1111/j.1469-7610.2004.00343.x

Bauermeister, J. J., Shrout, P. E., Ramírez, R., Bravo, M., Alegría, M., Martínez-Taboas, A., . . . Canino, G. (2007). ADHD correlates, comorbidity, and impairment in community and treated samples of children and adolescents. *Journal of Abnormal Child Psychology, 35*(6), 883-898. doi:10.1007/s10802-007-9141-4

Bell, R. Q. (1968). Adaptation of small wrist watches for mechanical recording of activity in infants and children. *Journal of Experimental Child Psychology, 6*(2), 302-305. doi:10.1016/0022-0965(68)90093-3

Bell, R. Q., Waldrop, M. F., & Weller, G. M. (1972). A rating system for the assessment of hyperactive and withdrawn children in preschool samples. *American Journal of Orthopsychiatry, 42*(1), 23-34. doi:10.1111/j.1939-0025.1972.tb02467.x

Berwid, O. G., Curko Kera, E. A., Marks, D. J., Santra, A., Bender, H. A., & Halperin, J. M. (2005). Sustained attention and response inhibition in young children at risk for attention deficit/hyperactivity disorder. *Journal of Child Psychology and Psychiatry, 46*(11), 1219-1229. doi:10.1111/j.1469-7610.2005.00417.x

Biederman, J., Kwon, A., Aleardi, M., Chouinard, V.-A., Marino, T., Cole, H., . . . Faraone, S. V. (2005). Absence of gender effects on attention deficit hyperactivity disorder: Findings in nonreferred subjects. *American Journal of Psychiatry, 162*(6), 1083-1089. doi:10.1176/appi.ajp.162.6.1083

Biederman, J., Mick, E., Faraone, S. V., Braaten, E., Doyle, A., Spencer, T., . . . Johnson, M. A. (2002). Influence of gender on attention deficit hyperactivity disorder in children referred to a psychiatric clinic. *American Journal of Psychiatry, 159*(1), 36-42. doi:10.1176/appi.ajp.159.1.36

Biederman, J., Wilens, T., Mick, E., Faraone, S. V., Weber, W., Curtis, S., . . . Soriano, J. (1997). Is ADHD a risk factor for psychoactive substance use disorders? Findings from a four-year prospective follow-up study. *Journal of the American Academy of Child & Adolescent Psychiatry, 36*(1), 21-29. doi: 10.1097/00004583-199701000-00013

Biederman, J., Wozniak, J., Kiely, K., Ablon, S., Faraone, S., Mick, E., . . . Kraus, I. (1995). CBCL clinical scales discriminate prepubertal children with structured interview-derived diagnosis of mania from those with ADHD. *Journal of the American Academy of Child & Adolescent Psychiatry, 34*(4), 464-471. doi:10.1097/00004583-199504000-00013

Birch, H. G. (1964). *Brain damage in children: The biological and social aspects*. Baltimore: Williams & Wilkins.

Birmaher, B., Ehmann, M., Axelson, D. A., Goldstein, B. I., Monk, K., Kalas, C., . . . Brent, D. A. (2009). Schedule for affective disorders and schizophrenia for school-age children (K-SADS-PL) for the assessment of preschool children – A preliminary psychometric study. *Journal of Psychiatric Research, 43*(7), 680-686. doi:10.1016/j.jpsychires.2008.10.003

Bourneville, D.-M. (1895). *Assistance, traitement et education des enfants idiots et dégénérés* (F.Alean, Ed.). Paris: Progrès Médical.

Broggin, E., Savazzi, S., & Marzi, C. A. (2012). Similar effects of visual perception and imagery on simple reaction time. *The Quarterly Journal of Experimental Psychology, 65*(1), 151-164. doi:10.1080/17470218.2011.594896

Brook, J. S., Brook, D. W., Zhang, C., Seltzer, N., & Finch, S. J. (2013). Adolescent ADHD and adult physical and mental health, work performance, and financial stress. *Pediatrics, 131*(1), 5-13. doi:10.1542/peds.2012-1725

Bull, R., Espy, K. A., & Wiebe, S. A. (2008). Short-term memory, working memory, and executive functioning in preschoolers: Longitudinal predictors of mathematical achievement at age 7 years. *Developmental Neuropsychology, 33*(3), 205-228. doi:10.1080/87565640801982312

Carlson, C. (1986). Attention deficit disorder without hyperactivity: A review of preliminary experimental evidence. In B.Lahey & A.Kazdin (Eds.), *Advances in clinical child psychology* (Vol. 9, pp. 153-176). New York: Plenum Press.

Castellanos, F. X., Sonuga-Barke, E. J. S., Scheres, A., Di Martino, A., Hyde, C., & Walters, J. R. (2005). Varieties of ADHD-related intra-individual variability. *Biological Psychiatry*, 57, 1416–1423.

Chess, S. (1960). Diagnosis and treatment of the hyperactive child. *New York State Journal of Medicine*, *60*, 2379–2385

Clements S. D., & Peters, J. E. (1962). Minimal brain dysfunctions in the school-age child: Diagnosis and treatment. *Archives of General Psychiatry.* 6:185–197

Clouston, T. S. (1899).Stages of over-excitability, hypersensitiveness and mental explosiveness in children and their treatment by the bromides. *Scottish Medical and Surgical Journal*, 4, 481-490.

Cohen, J. (1992). A power primer. *Psychological Bulletin, 112*(1), 155-159. doi:10.1037/0033-2909.112.1.155

Colle, H. A., & Welsh, A. (1976). Acoustic masking in primary memory. *Journal of Verbal Learning and Verbal Behavior, 15*(1), 17-31. doi:10.1016/S0022-5371(76)90003-7

Conners, C. K. (2008). *Conners 3rd Edition (Conners 3)*. Los Angeles, CA: Multi-Health

Systems, Inc (MHS).

Conrad, R., & Hull, A. J. (1964). Information, acoustic confusion and memory span. *British Journal of Psychology, 55*(4), 429-432. doi:10.1111/j.2044-8295.1964.tb00928.x

Crichton A. (1798). *An inquiry into the nature and origin of mental derangement: Comprehending a concise system of the physiology and pathology of the human mind and a history of the passions and their effects*. London, England: T. Cadell Hr. & W. Davies. (Reprinted by AMS Press, New York, 1976)

Conway, A. R. A., Kane, M. J., Bunting, M. F., Hambrick, D. Z., Wilhelm, O., & Engle, R. W. (2005). Working memory span tasks: A methodological review and user's guide. *Psychonomic Bulletin & Review, 12*(5), 769-786. doi:10.3758/BF03196772

Dane, A. V., Schachar, R. J., & Tannock, R. (2000). Does actigraphy differentiate ADHD subtypes in a clinical research setting? *Journal of the American Academy of Child & Adolescent Psychiatry, 39*(6), 752-760. doi:10.1097/00004583-200006000-00014

deHaas, P. A. (1986). Attention styles and peer relationships of hyperactive and normal boys and girls. *Journal of Abnormal Child Psychology, 14*(3), 457-467. doi:10.1007/BF00915438

Douglas, V. I. (1980). Higher mental processes in hyperactive children: Implications for training. In R. Knights & D. Bakker (Eds.), *Treatment of hyperactive and learning disordered children* (pp. 283-318). New York: Academic Press.

Dumenci, L., McConaughy, S. H., & Achenbach, T. M. (2004). A hierarchical three-factor model of inattention- hyperactivity-impulsivity derived from the attention problems syndrome of the teacher's report form. *School Psychology Review, 33*(2), 287-301.

Engle, R. W., Tuholski, S. W., Laughlin, J. E., & Conway, A. R. (1999). Working memory, short-term memory, and general fluid intelligence: A latent-variable approach. *Journal of experimental psychology. General, 128*(3), 309-331. doi:10.1037//0096-3445.128.3.309

Faraone, S. V., Biederman, J., & Mick, E. (2006). The age-dependent decline of attention deficit hyperactivity disorder: a meta-analysis of follow-up studies. *Psychological Medicine, 36*(02), 159-165. doi:doi:10.1017/S003329170500471X

Faraone, S. V., Biederman, J., Spencer, T., Mick, E., Murray, K., Petty, C., . . . Monuteaux, M. C. (2006). Diagnosing adult attention deficit hyperactivity disorder: Are late onset and subthreshold diagnoses valid? *American Journal of Psychiatry, 163*(10), 1720-1729. doi:10.1176/ajp.2006.163.10.1720

Fassbender, C., & Schweitzer, J. B. (2006). Is there evidence for neural compensation in attention deficit hyperactivity disorder? A review of the functional neuroimaging literature. *Clinical Psychology Review, 26*(4), 445-465. doi:10.1016/j.cpr.2006.01.003

Faul, F., Erdfelder, E., Lang, A. G., & Buchner, A. (2007). G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods, 39*, 175-191.

Fergusson, D. M., Lynskey, M. T., & Horwood, L. J. (1997). Attentional difficulties in middle childhood and psychosocial outcomes in young adulthood. *Child Psychology & Psychiatry & Allied Disciplines, 38*(6), 633-644.

doi:10.1111/j.1469-7610.1997.tb01690.x

Frazier, T. W., Youngstrom, E. A., Glutting, J. J., & Watkins, M. W. (2007). ADHD and achievement: Meta-analysis of the child, adolescent, and adult literatures and a concomitant study with college students. *Journal of Learning Disabilities, 40*(1), 49-65. doi:10.1177/00222194070400010401

Friedman, L. M., Rapport, M. D., Orban, S. A., Eckrich, S. J., & Calub, C. A. (2017). Applied problem solving in children with ADHD: The mediating roles of working memory and mathematical calculation. *Journal of Abnormal Child Psychology*. doi:10.1007/s10802-017-0312-7

Gathercole, S. E., Alloway, T. P., Kirkwood, H. J., Elliott, J. G., Holmes, J., & Hilton, K. A. (2008). Attentional and executive function behaviours in children with poor working memory. *Learning and Individual Differences, 18*(2), 214-223. doi:10.1016/j.lindif.2007.10.003

Gaub, M., & Carlson, C. L. (1997). Gender differences in ADHD: A meta-analysis and critical review. *Journal of the American Academy of Child & Adolescent Psychiatry, 36*(8), 1036-1045. doi:10.1097/00004583-199708000-00011

Gershon, J. (2002). A meta-analytic review of gender differences in ADHD. *Journal of Attention Disorders, 5*(3), 143-154. doi:10.1177/108705470200500302

Ghanizadeh, A. (2012). Psychometric analysis of the new ADHD DSM-V derived symptoms. *BMC Psychiatry, 12*(1), 21. doi:10.1186/1471-244X-12-21

Gooding, P. A., Isaac, C. L., & Mayes, A. R. (2005). Prose recall and amnesia: More implications for the episodic buffer. *Neuropsychologia, 43*(4), 583-587. doi:10.1016/j.neuropsychologia.2004.07.004

Graetz, B. W., Sawyer, M. G., & Baghurst, P. (2005). Gender differences among children with DSM-IV ADHD in Australia. *Journal of the American Academy of Child & Adolescent Psychiatry, 44*(2), 159-168. doi:10.1097/00004583-200502000-00008

Gray, J. A. (1982). *The neuropsychology of anxiety: An enquiry into the functions of the septo-hippocampal system*. New York, NY, US: Clarendon Press/Oxford University Press.

Gualtieri, C. T., & Johnson, L. G. (2005). ADHD: Is Objective Diagnosis Possible? *Psychiatry (Edgmont), 2*(11), 44-53.

Halperin, J. M., & Schulz, K. P. (2006). Revisiting the role of the prefrontal cortex in the pathophysiology of attention-deficit/hyperactivity disorder. *Psychological Bulletin, 132*(4), 560-581. doi:10.1037/0033-2909.132.4.560

Halverson, C. F., & Waldrop, M. F. (1973). The relations of mechanically recorded activity level to varieties of preschool play behavior. *Child Development, 44*(3), 678-681. doi:10.2307/1128031

Hartanto, T. A., Krafft, C. E., Iosif, A. M., & Schweitzer, J. B. (2016). A trial-by-trial analysis reveals more intense physical activity is associated with better cognitive control performance in attention-deficit/hyperactivity disorder. *Child Neuropsychology, 22*(5), 618-626. doi:10.1080/09297049.2015.1044511

Herbert, M. (1964). The concept and testing of brain damage in children: A review. *Journal of Child Psychology and Psychiatry*, *5*, 197–217.

Hoffman, H. (1865). *Die Geschichte vom Zappel-Philipp[Fidgetty Phil]*. In H.Hoffman,Der Struwwelpeter [Shockheaded Peter]. Erlangen, Germany: Pestalozzi-Verlag.

Horn, W. F., Wagner, A. E., & Lalongo, N. (1989). Sex differences in school-aged children with pervasive attention deficit hyperactivity disorder. *Journal of Abnormal Child Psychology, 17*(1), 109-125. doi:10.1007/BF00910773

Hoza, B. (2007). Peer functioning in children with ADHD. *Journal of Pediatric Psychology, 32*(6), 655-663. doi:10.1093/jpepsy/jsm024

Huang-Pollock, C., Shapiro, Z., Galloway-Long, H., & Weigard, A. (2016). Is Poor Working Memory a Transdiagnostic Risk Factor for Psychopathology? *Journal of Abnormal Child Psychology*. doi:10.1007/s10802-016-0219-8

Hudec, K. L., Alderson, R. M., Patros, C. H. G., Lea, S. E., Tarle, S. J., & Kasper, L. J. (2015). Hyperactivity in boys with attention-deficit/hyperactivity disorder (ADHD): The role of executive and non-executive functions. *Research in Developmental Disabilities, 45-46*, 103-109. doi:10.1016/j.ridd.2015.07.012

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*(3), 209-224. doi:10.1080/09297049.2010.532204

James W. (1890). *The principles of psychology*. London, England: Dover.

James, A., & Taylor, E. (1990). Sex differences in the hyperkinetic syndrome of childhood. *Journal of Child Psychology and Psychiatry, 31*(3), 437-446.

doi:10.1111/j.1469-7610.1990.tb01580.x

Karlsen, P. J., Allen, R. J., Baddeley, A. D., & Hitch, G. J. (2010). Binding across space and time in visual working memory. *Memory & Cognition, 38*(3), 292-303. doi:10.3758/MC.38.3.292

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*(7), 605-617. doi:10.1016/j.cpr.2012.07.001

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*(7), 980-988. doi: 10.1097/00004583-199707000-00021

Kaufman, A. S., & Kaufman, N. L. (2014). *Kaufman test of educational achievement, third edition*. Bloomington, MN: NCS: Pearson.

Kaufman, A. S., Kaufman, N. L., & (with Breaux, N. C.) (2014). Technical and Interpretive Manual *Kaufman test of educational achievement, third edition*. Bloomington, MN: NCS Pearson.

Kessler, J. W. (1980). History of minimal brain dysfunction. In H. Rie & E. Rie (Eds.), *Handbook of minimal brain dysfunctions: A critical view.* 18–52. New York: Wiley

Kessler, R. C., Adler, L., Barkley, R., Biederman, J., Conners, C. K., Demler, O., . . . Zaslavsky, A. M. (2006). The prevalence and correlates of adult ADHD in the

United States: results from the national comorbidity survey replication. *American Journal of Psychiatry, 163*(4), 716-723. doi:10.1176/ajp.2006.163.4.716

Klauer, K. C., & Zhao, Z. (2004). Double dissociations in visual and spatial short-term memory. *Journal of Experimental Psychology, Generall, 133*(3), 355-381. doi:10.1037/0096-3445.133.3.355

Klein, R. G., Mannuzza, S., Ramos Olazagasti, M. A., Roizen Belsky, E., Hutchison, J. A., Lashua-Shriftman, E., & Castellanos, F. X. (2012). Clinical and functional outcome of childhood ADHD 33 years later. *Archives of General Psychiatry, 69*(12), 1295-1303. doi:10.1001/archgenpsychiatry.2012.271

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*(3), 459-471. doi:10.1037/neu0000050

Kofler, M. J., Raiker, J. S., Sarver, D. E., Wells, E. L., & Soto, E. F. (2016). Is hyperactivity ubiquitous in ADHD or dependent on environmental demands? Evidence from meta-analysis. *Clinical Psychology Review, 46*, 12-24. doi:10.1016/j.cpr.2016.04.004

Kofler, M. J., Rapport, M. D., Bolden, J., Sarver, D. E., Raiker, J. S., & Alderson, R. M. (2011). Working memory deficits and social problems in children with ADHD. *Journal of Abnormal Child Psychology, 39*(6), 805-817. doi:10.1007/s10802-011-9492-8

Konofal, E., Lecendreux, M., Bouvard, M. P., & Mouren-Simeoni, M.-C. (2001). High levels of nocturnal activity in children with attention-deficit hyperactivity disorder: A video analysis. *Psychiatry and Clinical Neurosciences, 55*(2), 97-103. doi:10.1046/j.1440-1819.2001.00808.x

Kovacs, M. (2003). *Children's Depression Inventory (CDI): Technical Manual Update*. North Tonawanda, NY: Multi-Health Systems, Inc.

Lahey, B. B., & Carlson, C. L. (1992).Validity of the diagnostic category of attention deficit disorder without hyperactivity: A review of the literature. In S. E.Shaywitz & B. A. Shaywitz (Eds.), *Attention deficit disorder comes of age: Toward the twenty-first century* (pp. 119-144). Austin, TX: Pro-Ed.

Lahey, B. B., Pelham, W. E., Loney, J., Lee, S. S., & Willcutt, E. (2005). Instability of the DSM-IV subtypes of ADHD from preschool through elementary school. *Archives of General Psychiatry, 62*(8), 896-902. doi:10.1001/archpsyc.62.8.896

Lange, K. W., Reichl, S., Lange, K. M., Tucha, L., & Tucha, O. (2010). The history of attention deficit hyperactivity disorder. *Attention Deficit and Hyperactivity Disorders, 2*(4), 241-255. doi:10.1007/s12402-010-0045-8

Larsson, H., Chang, Z., D'Onofrio, B. M., & Lichtenstein, P. (2013). The heritability of clinically diagnosed attention deficit hyperactivity disorder across the lifespan. *Psychological Medicine, 44*(10), 2223-2229. doi:10.1017/S0033291713002493

Laufer, M., Denhoff, E., & Solomons, G. (1957). Hyperkinetic impulse disorder in children's behavior problems. *Psychosomatic Medicine*, *19*, 38–49.

Logan, G. D., & Cowan, W. B. (1984). On the ability to inhibit thought and action: A theory of an act of control. *Psychological Review, 91*(3), 295-327. doi:10.1037/0033-295X.91.3.295

Logie, R. H., Del Sala, S., Wynn, V., & Baddeley, A. D. (2000). Visual similarity effects in immediate verbal serial recall. *The Quarterly Journal of Experimental Psychology Section A, 53*(3), 626-646. doi:10.1080/713755916

Loney, J., Langhorne, J. E., & Paternite, C. E. (1978). An empirical basis for subgrouping the hyperkinetic/minimal brain dysfunction syndrome. *Journal of Abnormal Psychology, 87*(4), 431-441. doi:10.1037/0021-843X.87.4.431

Luck, S. J., & Vogel, E. K. (1997). The capacity of visual working memory for features and conjunctions. *Nature, 390*(6657), 279-281.

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: A latent variable analysis. *Cognitive Psychology, 41*(1), 49-100. doi:10.1006/cogp.1999.0734

Marks, D. J., Berwid, O. G., Santra, A., Kera, E. C., Cyrulnik, S. E., & Halperin, J. M. (2005). Neuropsychological correlates of ADHD symptoms in preschoolers. *Neuropsychology, 19*(4), 446-455. doi:10.1037/0894-4105.19.4.446

Martel, M. M., Roberts, B., Gremillion, M., von Eye, A., & Nigg, J. T. (2011). External validation of bifactor model of ADHD: Explaining heterogeneity in psychiatric comorbidity, cognitive control, and personality trait profiles within DSM-IV ADHD. *Journal of Abnormal Child Psychology, 39*(8), 1111. doi:10.1007/s10802-011-9538-y

Martel, M. M., von Eye, A., & Nigg, J. (2012). Developmental differences in structure of attention-deficit/hyperactivity disorder (ADHD) between childhood and adulthood. *International Journal of Behavioral Development, 36*(4), 279-292. doi:10.1177/0165025412444077

Martel, M. M., von Eye, A., & Nigg, J. T. (2010). Revisiting the latent structure of ADHD: is there a ‘g’ factor? *Journal of Child Psychology and Psychiatry, 51*(8), 905-914. doi:10.1111/j.1469-7610.2010.02232.x

Martinussen, R., Hayden, J., Hogg-Johnson, S., & Tannock, R. A meta-analysis of working memory impairments in children with attention-deficit/hyperactivity disorder. *Journal of the American Academy of Child & Adolescent Psychiatry, 44*(4), 377-384. doi:10.1097/01.chi.0000153228.72591.73

Massey, P. S., Lieberman, A., & Bartesh, G. (1971). Measure of activity level in mentally retarded children and adolescents. *American Journal of Mental Deficiency, 76*, 259-261.

McAuley, T., Chen, S., Goos, L., Schachar, R., & Crosbie, J. (2010). Is the Behavior Rating Inventory of Executive Function more strongly associated with measures of impairment or executive function? *Journal of the International Neuropsychological Society, 16*(3), 495-505. doi:10.1017/S1355617710000093

Miyahara, M., Healey, D. M., & Halperin, J. M. (2014). One-week temporal stability of hyperactivity in preschoolers with ADHD during psychometric assessment. *Psychiatry and Clinical Neurosciences, 68*(2), 120-126. doi:10.1111/pcn.12096

Moleiro, C., Madureira, S., Verdelho, A., Ferro, J. M., Poggesi, A., Chabriat, H., . . . Inzitari, D. (2013). Confirmatory factor analysis of the Neuropsychological Assessment Battery of the LADIS study: A longitudinal analysis. *Journal of Clinical and Experimental Neuropsychology, 35*(3), 269-278. doi:10.1080/13803395.2013.770822

Molina, B. S. G., & Pelham, W. E., Jr. (2003). Childhood predictors of adolescent substance use in a longitudinal study of children with ADHD. *Journal of Abnormal Psychology, 112*(3), 497-507. doi:10.1037/0021-843X.112.3.497

Morgenthaler, T., Alessi, C., Friedman, L., Owens, J., Kapur, V., Boehlecke, B., . . . Swick, T. J. (2007). Practice Parameters for the Use of Actigraphy in the Assessment of Sleep and Sleep Disorders: An Update for 2007. *Sleep, 30*(4), 519-529. doi:10.1093/sleep/30.4.519

Murray, D. J. (1968). Articulation and acoustic confusability in short-term memory. *Journal of Experimental Psychology, 78*(4, Pt.1), 679-684. doi:10.1037/h0026641

Nikolas, M. A., & Burt, S. A. (2010). Genetic and environmental influences on ADHD symptom dimensions of inattention and hyperactivity: A meta-analysis. *Journal of Abnormal Psychology, 119*(1), 1-17. doi:10.1037/a0018010

Noldus Information Technology. (2008). *The Observer XT reference manual 8.0*. Wageningen, Netherlands: Author.

Ostrander, R., Weinfurt, K. P., Yarnold, P. R., & August, G. J. (1998). Diagnosing attention deficit disorders with the Behavioral Assessment System for Children and the Child Behavior Checklist: Test and construct validity analyses using optimal discriminant classification trees. *Journal of Consulting and Clinical Psychology, 66*(4), 660-672. doi:10.1037/0022-006X.66.4.660

Partington, M. W., Lang, E., & Campbell, D. (1971). Motor Activity in Early Life. I. Fries' Congenital Activity Types. *Neonatology, 18*(1-2), 94-107.

Patros, C. H. G., Alderson, R. M., Hudec, K. L., Tarle, S. J., & Lea, S. E. (2017). Hyperactivity in boys with attention-deficit/hyperactivity disorder: The influence of underlying visuospatial working memory and self-control processes. *Journal of*

Experimental Child Psychology, 154, 1-12. doi:10.1016/j.jecp.2016.09.008

Patros, C. H. G., Alderson, R. M., Lea, S. E., Tarle, S. J., Kasper, L. J., & Hudec, K. L. (2015). Visuospatial working memory underlies choice-impulsivity in boys with attention-deficit/hyperactivity disorder. *Research in Developmental Disabilities*, *38,* 134-144. doi:10.1016/j.ridd.2014.12.016.

Pelham, J. W. E., Fabiano, G. A., & Massetti, G. M. (2005). Evidence-Based Assessment of Attention Deficit Hyperactivity Disorder in Children and Adolescents. *Journal of Clinical Child & Adolescent Psychology, 34*(3), 449-476. doi:10.1207/s15374424jccp3403_5

Pennington, B. F., & Ozonoff, S. (1996). Executive functions and developmental psychopathology. *Journal of Child Psychology and Psychiatry, 37*(1), 51-87. doi:10.1111/j.1469-7610.1996.tb01380.x

Plomin, R., & Foch, T. T. (1981). Hyperactivity and pediatrician diagnoses, parental ratings, specific cognitive abilities, and laboratory measures. *Journal of Abnormal Child Psychology, 9*(1), 55-64. doi:10.1007/BF00917857

Polanczyk, G., de Lima, M. S., Horta, B. L., Biederman, J., & Rohde, L. A. (2007). The Worldwide Prevalence of ADHD: A Systematic Review and Metaregression Analysis. *American Journal of Psychiatry, 164*(6), 942-948. doi:10.1176/ajp.2007.164.6.942

Polanczyk, G. V., Willcutt, E. G., Salum, G. A., Kieling, C., & Rohde, L. A. (2014). ADHD prevalence estimates across three decades: an updated systematic review and meta-regression analysis. *International Journal of Epidemiology, 43*(2), 434-442. doi:10.1093/ije/dyt261

Porrino, L. J., Rapoport, J. L., Behar, D., Sceery, W., Ismond, D. R., Bunney, W. E., & Jr. (1983). A naturalistic assessment of the motor activity of hyperactive boys: I. comparison with normal controls. *Archives of General Psychiatry, 40*(6), 681-687. doi:10.1001/archpsyc.1983.04390010091012

Quay, H. C. (1997). Inhibition and attention deficit hyperactivity disorder. *Journal of Abnormal Child Psychology, 25*(1), 7-13. doi:10.1023/A:1025799122529

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*(5), 699-713. doi:10.1007/s10802-011-9607-2

Ramtekkar, U. P., Reiersen, A. M., Todorov, A. A., & Todd, R. D. (2010). Sex and age differences in attention-deficit/hyperactivity disorder symptoms and diagnoses: Implications for DSM-V and ICD-11. *Journal of the American Academy of Child & Adolescent Psychiatry, 49*(3), 217-228. doi:10.1097/00004583-201003000-00005

Rapin, I. (1964). Brain damage in children. In J. Brennemann (Ed.), *Practice of pediatrics* (Vol. 4). Hagerstown, MD: Prior.

Rapoport, J., Abramson, A., Alexander, D., & Lott, I. (1971). Playroom observations of hyperactive children on medication. *Journal of the American Academy of Child Psychiatry, 10*(3), 524-534. doi:10.1016/S0002-7138(09)61754-4

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*(6), 825-837. doi:10.1007/s10802-008-9215-y

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*(4), 521-534. doi:10.1007/s10802-008-9287-8

Rapport, M. D., Chung, K.-M., Shore, G., & Isaacs, P. (2001). A conceptual model of child psychopathology: Implications for understanding attention deficit hyperactivity disorder and treatment efficacy. *Journal of Clinical Child Psychology, 30*(1), 48-58. doi:10.1207/S15374424JCCP3001_6

Rapport, M. D., Kofler, M. J., Alderson, R. M., & Raiker, J. S. (2008). Attention-Deficit/Hyperactivity Disorder. In M. Hersen & J. Rosqvist (Eds.), *Handbook of Psychological Assessment, Case Conceptualization, and Treatment* (Vol. Volume 2: Children and Adolescents, pp. 349-404). Hoboken, NJ: Wiley & Sons.

Rapport, M. D., Kofler, M. J., & Himmerich, C. (2006). Assessing activity level in children. In M. Hersen (Ed.), *Clinician's Handbook of Child Behavioral Assessment* (pp. 125-157). San Diego, CA: Elsevier Inc.

Reynolds, C. R., & Richmond, B. O. (2008). *Revised Children's Manifest Anxiety Scale-2 (RCMAS-2) Second Edition Manual*. Los Angeles, CA: Western Psychological Services.

Roberts, W., Milich, R., & Barkley, R. A. (2015). Primary symptoms, diagnostic criteria, subtyping, and prevalence of ADHD. In R. A. Barkley & R. A. Barkley (Eds.), *Attention-deficit hyperactivity disorder: A handbook for diagnosis and treatment.* (pp. 51-80). New York, NY, US: Guilford Press.

Rogers, M., Hwang, H., Toplak, M., Weiss, M., & Tannock, R. (2011). Inattention, working memory, and academic achievement in adolescents referred for attention deficit/hyperactivity disorder (ADHD). *Child Neuropsychology, 17*(5), 444-458. doi:10.1080/09297049.2010.544648

Ross, D. M., & Ross, S. A. (1976). *Hyperactivity: Research, theory and action*. Wiley, New York

Rossi-Arnaud, C., Pieroni, L., & Baddeley, A. (2006). Symmetry and binding in visuo-spatial working memory. *Neuroscience, 139*(1), 393-400. doi:10.1016/j.neuroscience.2005.10.048

Rudner, M., Fransson, P., Ingvar, M., Nyberg, L., & Rönnberg, J. (2007). Neural representation of binding lexical signs and words in the episodic buffer of working memory. *Neuropsychologia, 45*(10), 2258-2276. doi:10.1016j.neuropsychologia.2007.02.017

Salamé, P., & Baddeley, A. (1990). The effects of irrelevant speech on immediate free recall. *Bulletin of the Psychonomic Society, 28*(6), 540-542. doi:10.3758/BF03334073

Sanders, A. F. (1983). Towards a model of stress and human performance. *Acta Psychologica, 53*(1), 61-97. doi:10.1016/0001-6918(83)90016-1

Schachar, R., & Logan, G. D. (1990). Impulsivity and inhibitory control in normal development and childhood psychopathology. *Developmental Psychology, 26*(5), 710-720. doi:10.1037/0012-1649.26.5.710

Sergeant, J. (2000). The cognitive-energetic model: An empirical approach to attention-deficit hyperactivity disorder. *Neuroscience and Biobehavioral Reviews, 24*(1), 7-12. doi:10.1016/S0149-7634(99)00060-3

Sergeant, J. A. (2005). Modeling Attention-Deficit/Hyperactivity Disorder: A critical appraisal of the cognitive-energetic model. *Biological Psychiatry, 57*(11), 1248-1255. doi:10.1016/j.biopsych.2004.09.010

Sergeant, J. A., Oosterlaan, J., & van der Meere, J. (1999). Information processing and energetic factors in attention-deficit/hyperactivity disorder. In H. C. Quay, A. E. Hogan, H. C. Quay, & A. E. Hogan (Eds.), *Handbook of disruptive behavior disorders.* (pp. 75-104). Dordrecht, Netherlands: Kluwer Academic Publishers.

Simone, A. N., Marks, D. J., Bédard, A.-C., & Halperin, J. M. (2017). Low working memory rather than ADHD symptoms predicts poor academic achievement in school-aged children. *Journal of Abnormal Child Psychology*. doi:10.1007/s10802-017-0288-3

Skounti, M., Philalithis, A., & Galanakis, E. (2007). Variations in prevalence of attention deficit hyperactivity disorder worldwide. *European Journal of Pediatrics, 166*(2), 117-123. doi:10.1007/s00431-006-0299-5

Smith, E. E., & Jonides, J. (1997). Working memory: A view from neuroimaging. *Cognitive Psychology, 33*(1), 5-42. doi:10.1006/cogp.1997.0658

Smith, E. E., Jonides, J., & Koeppe, R. A. (1996). Dissociating verbal and spatial working memory using PET. *Cerebral Cortex, 6*(1), 11-20. doi:10.1093/cercor/6.1.11

Solanto, M. V., Abikoff, H., Sonuga-Barke, E. J. S., Schachar R, Logan G. D., Wigal, T., et al (2001): The ecological validity of delay aversion and response inhibition as measures of impulsivity in AD/HD: A supplement to the NIMH multimodal treatment study of AD/HD. *Journal of Abnormal Child Psychology.* 29:215–228.

Solanto, M. V., Wasserstein, J., Marks, D. J., & Mitchell, K. J. (2011). Diagnosis of ADHD in adults. *Journal of Attention Disorders, 16*(8), 631-634. doi:10.1177/1087054711416910

Sonuga-Barke, E. J. S. (1994). On dysfunction and function in psychological theories of childhood disorder. *Journal of Child Psychology and Psychiatry,* 35:801– 815.

Sonuga-Barke, E. J. S. (2003). The dual pathway model of AD/HD: An elaboration of neuro-developmental characteristics. *Neuroscience and Biobehavioral Reviews, 27*(7), 593-604. doi:10.1016/j.neubiorev.2003.08.005

Sonuga-Barke, E. J. S. (2005). Causal models of attention-deficit/hyperactivity disorder: from common simple deficits to multiple developmental pathways. *Biological Psychiatry, 57*(11), 1231-1238. doi:10.1016/j.biopsych.2004.09.008

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*(4), 345-355. doi:.1097/00004583-201004000-00009

Stevens, T. M., Kupst, M. J., Suran, B. G., & Schulman, J. L. (1978). Activity level: A comparison between actometer scores and observer ratings. *Journal of Abnormal Child Psychology, 6*(2), 163-173. doi:10.1007/BF00919122

Still G. F. (1902). Some abnormal psychical conditions in children. *Lancet*, *i,* 1008-1012, 1077-1082, 1163-1168.

Strauss, A. A., & Lehtinen, L. E. (1947). *Psychopathology and education of the brain-injured child*. New York: Grune and Stratton.

SuperLab 4.0 [Computer program]. San Pedro, CA: Cedrus Corporation.

Swanson, J. M., Sergeant, J. A., Taylor, E., Sonuga-Barke, E. J. S., Jensen, P. S., & Cantwell, D. P. (1998). Attention-deficit hyperactivity disorder and hyperkinetic disorder. *The Lancet, 351*(9100), 429-433. doi: 10.1016/S0140-6736(97)11450-7

Szatmari, P., Offord, D. R., & Boyle, M. H. (1989). Ontario child health study: Prevalence of attention deficit disorder with hyperactivity. *Journal of Child Psychology and Psychiatry, 30*(2), 219-223. doi:10.1111/j.1469-7610.1989.tb00236.x

Tabachnick, B. G., & Fidell, L. S. (2001). *Using multivariate statistics (5th ed.)*. New York, NY: Pearson Inc.

Tamm, L., Narad, M. E., Antonini, T. N., O'Brien, K. M., Hawk, L. W., & Epstein, J. N. (2012). Reaction time variability in ADHD: A review. *Neurotherapeutics*, *9*(3), 500-508.doi:10.1007/s13311-012-0138-5

Tannock, R. (2012). Rethinking ADHD and LD in DSM-5: Proposed changes in diagnostic criteria. *Journal of Learning Disabilities, 46*(1), 5-25. doi:10.1177/0022219412464341

Tarle, S. J., Alderson, R. M., Patros, C. H. G., Lea, S. E., Hudec, K. L., & Arrington, E. F. (2017). Attention-deficit/hyperactivity disorder and phonological working memory: Methodological variability affects clinical and experimental performance metrics. *Neuropsychology, 31*(4), 383-394. doi:10.1037/neu0000364

Toplak, M. E., Bucciarelli, S. M., Jain, U., & Tannock, R. (2008). Executive functions: performance-based measures and the Behavior Rating Inventory of Executive Function (BRIEF) in adolescents with attention deficit/hyperactivity disorder (ADHD). *Child Neuropsychology, 15*(1), 53-72. doi:10.1080/09297040802070929

Toplak, M. E., Sorge, G. B., Flora, D. B., Chen, W., Banaschewski, T., Buitelaar, J., . . . Faraone, S. V. (2012). The hierarchical factor model of ADHD: Invariant across age and national groupings? *Journal of Child Psychology and Psychiatry, 53*(3), 292-303. doi:10.1111/j.1469-7610.2011.02500.x

Toplak, M. E., West, R. F., & Stanovich, K. E. (2013). Practitioner Review: Do performance-based measures and ratings of executive function assess the same construct? *Journal of Child Psychology and Psychiatry, 54*(2), 131-143. doi:10.1111/jcpp.12001

Tredgold, A. F. (1908). *Mental Deficiency (Amentia)*. New York: W. Wood.

Tryon, W. W. (1991). *Activity measurement in psychology and medicine.* New York: Plenum Press.

Tryon, W. W. (2008). Methods of measuring human activity. *Journal of Behavior Analysis in Health, Sports, Fitness and Medicine, 1*(1), 58-71. doi:10.1037/h0100369

Tryon, W. W. (2011). Actigraphy: The Ambulatory Measurement of Physical Activity. In J. K. Luiselli & D. D. Reed (Eds.), *Behavioral Sport Psychology: Evidence-Based Approaches to Performance Enhancement*. Springer New York: Dordrecht

Heidelberg London.

Tryon, W. W., & Pinto, L. P. (1994). Comparing activity measurements and ratings. *Behavior Modification, 18*(3), 251-261. doi:10.1177/01454455940183001

Unsworth, N., & Engle, R. W. (2007). The nature of individual differences in working memory capacity: active maintenance in primary memory and controlled search from secondary memory. *Psychological Review, 114*(1), 104-132. doi:10.1037/0033-295x.114.1.104

Vallar, G., & Baddeley, A. (1987). Phonological short-term store and sentence processing. *Cognitive Neuropsychology, 4*(4), 417-438. doi:10.1080/02643298708252046

van der Meere, J., Vreeling, H. J., & Sergeant, J. (1992). A motor presetting study in hyperactive, learning disabled and control children. *Journal of Child Psychology and Psychiatry, 33*(8), 1347-1351. doi:10.1111/j.1469-7610.1992.tb00954.x

Van Eck, K., Finney, S. J., & Evans, S. W. (2010). Parent report of ADHD symptoms of early adolescents: a confirmatory factor analysis of the disruptive behavior disorders scale. *Educational and Psychological Measurement, 70*(6), 1042-1059. doi:10.1177/0013164410378093

Vogel, E. K., Woodman, G. F., & Luck, S. J. (2001). Storage of features, conjunctions and objects in visual working memory. *Journal of Experimental Psychology. Human Perception and Performance, 27*(1), 92-114. doi:10.1037//0096-1523.27.1.92

Wang, S., Allen, R. J., Lee, J. R., & Hsieh, C.-E. (2015). Evaluating the developmental trajectory of the episodic buffer component of working memory and its relation to word recognition in children. *Journal of Experimental Child Psychology, 133*, 16-28. doi:10.1016/j.jecp.2015.01.002

Waschbusch, D. A. (2002). A meta-analytic examination of comorbid hyperactive-impulsive-attention problems and conduct problems. *Psychological Bulletin, 128*(1), 118-150.

Wechsler, D. (2002). Wechsler Preschool and Primary Scale of Intelligence--Third Edition: Pearson.

Wechsler, D. (2003). *Wechsler Intelligence Scale for Children* (4th ed.). San Antonio, TX: NCS Pearson.

Wechsler, D. (2014). *Wechsler Intelligence Scale for Children* (5th ed.). San Antonio, TX: NCS Pearson.

Weiss, M. D. (2010). The unique aspects of assessment of adult ADHD. *Primary Psychiatry*, *17*(5), 21-25.

Whalen, C. K., Henker, B., Collins, B. E., Finck, D., & Dotemoto, S. (1979). A social ecology of hyperactive boys: Medication effects in structured classroom environments. *Journal of Applied Behavior Analysis, 12*(1), 65-81. doi:10.1901/jaba.1979.12-65

Wheeler, M. E., & Treisman, A. M. (2002). Binding in short-term visual memory. *Journal of experimental psychology. General, 131*(1), 48-64. doi:10.1037//0096-3445.131.1.48

Wilens, T. E., Biederman, J., Brown, S., Tanguay, S., Monuteaux, M. C., Blake, C., & Spencer, T. J. (2002). Psychiatric comorbidity and functioning in clinically referred preschool children and school-age youths with ADHD. *Journal of the*

American Academy of Child & Adolescent Psychiatry, 41(3), 262-268. doi:10.1097/00004583-200203000-00005

Willcutt, E. G. (2012). The Prevalence of DSM-IV Attention-Deficit/Hyperactivity Disorder: A Meta-Analytic Review. *Neurotherapeutics, 9*(3), 490-499. doi:10.1007/s13311-012-0135-8

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*(11), 1336-1346. doi: 10.1016/j.biopsych.2005.02.006

Wolraich, M. L., Lambert, E. W., Baumgaertel, A., Garcia-Tornel, S., Feurer, I. D., Bickman, L., & Doffing, M. A. (2003). Teachers' screening for attention deficit/hyperactivity disorder: Comparing multinational samples on teacher ratings of ADHD. *Journal of Abnormal Child Psychology, 31*(4), 445-455. doi:10.1023/A:1023847719796

Figure 1. PH working memory task.

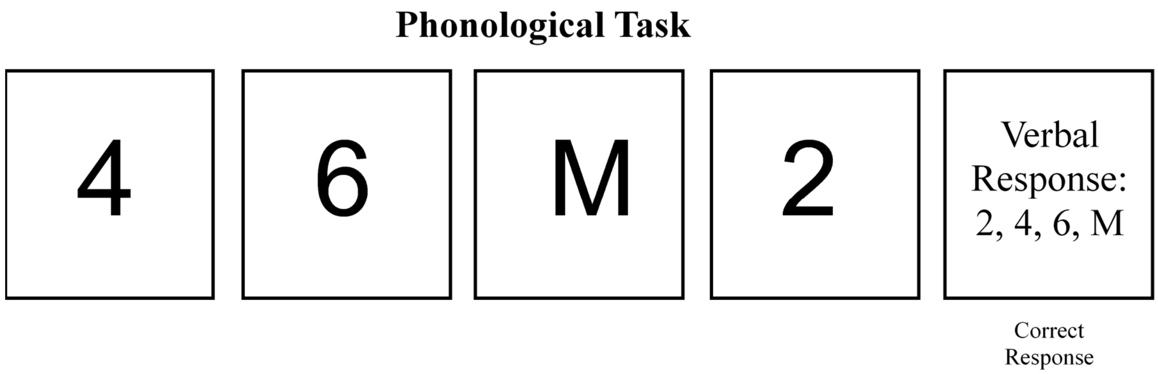


Figure 2. VS working memory task

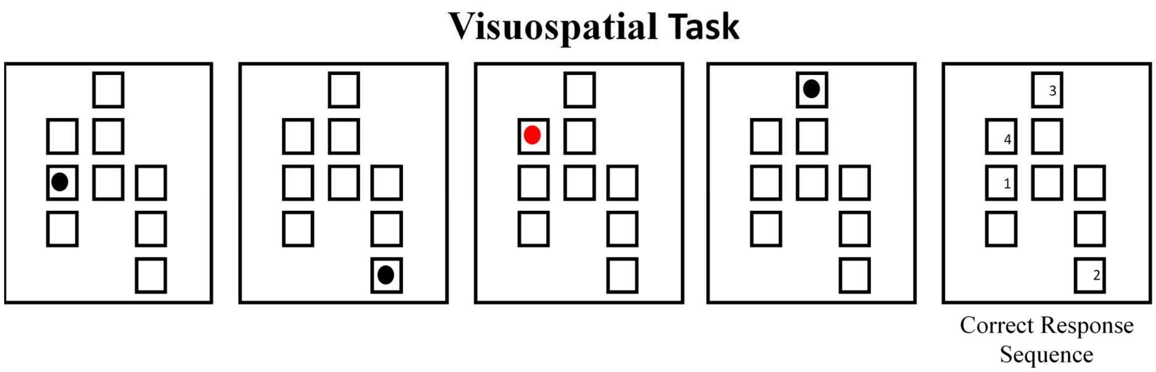


Figure 3. Blank response grid presented to participants in VS trials.

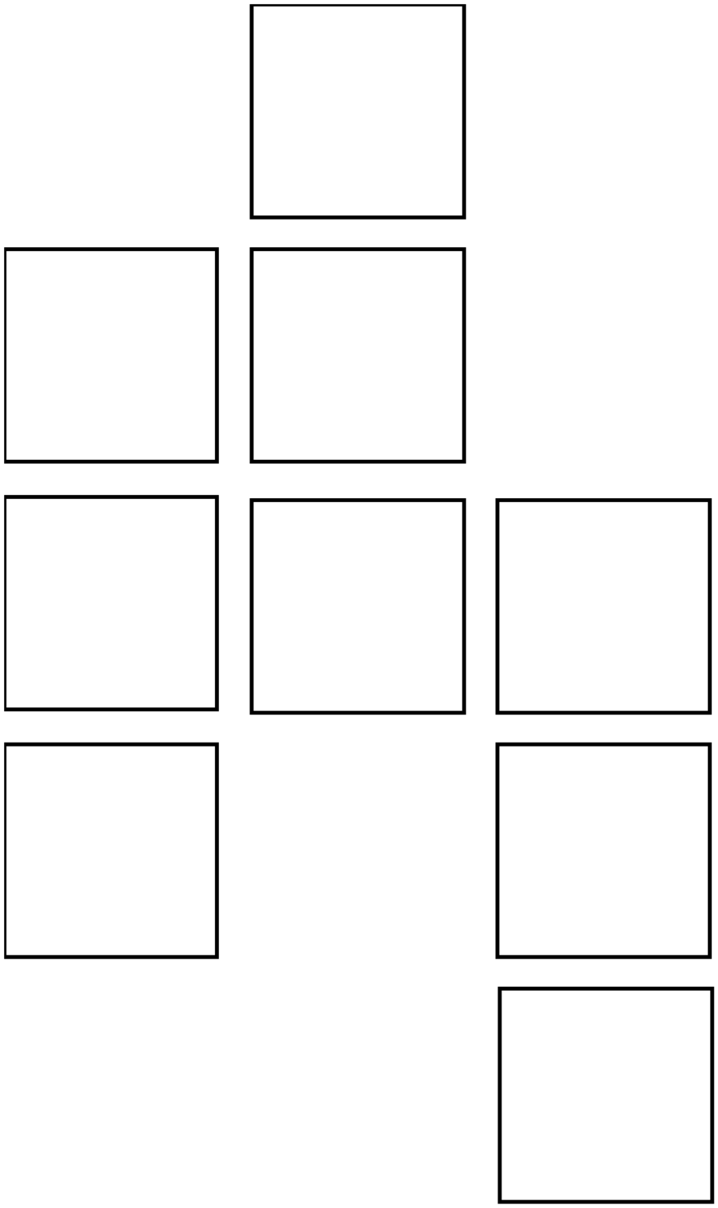
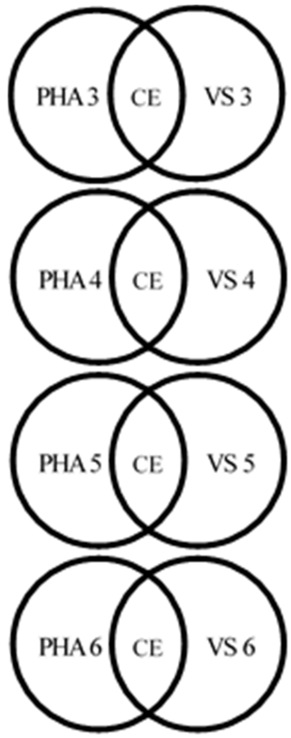
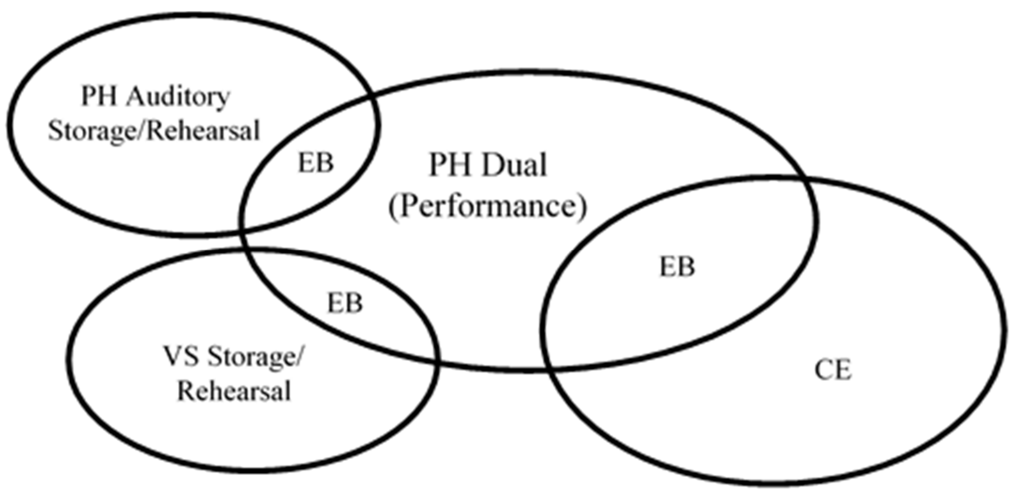


Figure 4. Working memory components derived from a regression approach

(a)



(b)



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