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# Impulsivity And Attention-Deficit/Hyperactivity Disorder (ADHD) Testing Competing Predictions From The Working Memory And Behavioral Inhibition Models Of Adhd

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# IMPULSIVITY AND ATTENTION-DEFICIT/HYPERACTIVITY DISORDER (ADHD): TESTING COMPETING PREDICTIONS FROM THE WORKING MEMORY AND BEHAVIORAL INHIBITION MODELS OF ADHD

by

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## ABSTRACT

Impulsivity is a hallmark of two of the three DSM-IV ADHD subtypes and is associated with myriad adverse outcomes. Limited research, however, is available concerning the mechanisms and processes that contribute to impulsive responding by children with ADHD. The current study tested predictions from two competing models of ADHD – working memory (WM) and behavioral inhibition (BI) – to examine the extent to which ADHD-related impulsive responding was attributable to model-specific mechanisms and processes. Children with ADHD ($n$ = 21) and typically developing children ($n$ = 20) completed laboratory tasks that provided WM (domain-general central executive [CE], phonological/visuospatial storage/rehearsal) and BI indices (stop-signal reaction time [SSRT], stop-signal delay, mean reaction time). These indices were examined as potential mediators of ADHD-related impulsive responding on two diverse laboratory tasks used commonly to assess impulsive responding (CPT: continuous performance test; VMTS: visual match-to-sample). Bias-corrected, bootstrapped mediation analyses revealed that CE processes significantly attenuated between-group impulsivity differences, such that the initial large-magnitude impulsivity differences were no longer significant on either task after accounting for ADHD-related CE deficits. In contrast, SSRT partially mediated ADHD-related impulsive responding on the CPT but not VMTS. This partial attenuation was no longer significant after accounting for shared variance between CE and SSRT; CE continued to attenuate the ADHD-impulsivity relationship after accounting for SSRT. These findings add to the growing literature implicating CE deficits in core ADHD behavioral and functional impairments, and suggest that cognitive interventions targeting CE rather than storage/rehearsal or BI processes may hold greater promise for alleviating ADHD-related impairments.

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| | |
|---|---|
| ADHD | Attention-Deficit/Hyperactivity Disorder |
| BI | Behavioral Inhibition |
| CBCL | Child Behavior Checklist |
| CE | Central Executive |
| CI | Confidence Interval |
| CLC | Children's Learning Clinic |
| CPT | Continuous Performance Tests |
| CSI-P | Child Symptom Inventory – 4: Parent Checklist |
| CSI-T | Child Symptom Inventory – 4: Teacher Checklist |
| DSM-IV | Diagnostic and Statistical Manual ($4^{th}$ Edition) |
| EF | Executive Function |
| ER | Effect Ratio |
| ES | Effect Size |
| FSIQ | Full Scale Intelligence Quotient |
| $FSIQ_{res}$ | Full Scale Intelligence Quotient Residual |
| IQ | Intelligent Quotient |
| K-SADS | Kiddie Schedule for Affective Disorders and Schizophrenia for School-Aged Children |
| MRT | Mean Reaction Time |
| ODD | Oppositional Defiant Disorder |

| | |
|---|---|
| PH | Phonological |
| SD | Standard Deviation |
| SE | Standard Error |
| SES | Socioeconomic Status |
| SSD | Stop-Signal Delay |
| SSRT | Stop-Signal Reaction Time |
| TRF | Teacher Report Form |
| VMTS | Visual Match-to-Sample |
| VS | Visuospatial |
| WISC | Wechsler Intelligence Scale for Children |
| WM | Working Memory |

# CHAPTER 1: INTRODUCTION

The ability to inhibit impulses and delay gratification is one of the earliest and most ubiquitous societal demands placed on children. Deficits in these abilities are particularly salient in children with attention-deficit/hyperactivity disorder (ADHD) and constitute one of the three primary symptom clusters of the disorder (APA, 2000). As a core component, the impulsivity construct refers to diverse actions that are performed without sufficient forethought and frequently result in undesirable consequences, including errors on academic assignments and cognitive tasks.

Identifying underlying mechanisms and processes that contribute to impulsive behavior in children with ADHD is imperative given its high heritability (McLoughlin, Ronald, Kuntsi, Asherson, & Plomin, 2007; Nikolas & Burt, 2010; Oades et al., 2008; Sherman, Iacono, & McGue, 1997), developmental continuity, and association with undesirable consequences throughout life. During childhood, adverse consequences associated with impulsive behavior include an increased risk for mishaps (Palili, Kolaitis, Vassi, Veltsista, Bakoula, & Gika, 2011), excessive errors on schoolwork and homework (Zentall, 1993), peer relational difficulties (Diamantopoulou, Rydell, Thorell, & Bohlin, 2007), and higher rates of oppositional defiant symptoms (Burns & Walsh, 2002). In later years, its continuation portends poor financial planning and lower SES (Moffitt et al., 2010), deficient driving behavior (Barkley, 2004), earlier/riskier sexual activity, unstable relationships, and impaired occupational functioning (Barkley, Fischer, Smallish, & Fletcher, 2006), as well as increased risk for substance use/abuse (Moffitt et al., 2010; Molina, Smith, & Pelham, 1999; Rodriguez, Tercyak, & Audrain-

McGovern, 2007), antisocial behavior (Babinski, Hartsough, & Lambert, 1999), and adult criminal conviction (Moffitt et al., 2010).

Impulsive behavior by children with ADHD is quantified objectively by measuring commission errors on laboratory-based tasks that require children to evaluate stimuli in an efficient manner. Commission errors refer to discrete instances in which children respond incorrectly to non-target stimuli, and demonstrate strong convergent validity with diverse indices of impulsivity. These indices include parent ratings (Avila, Cuenca, Félix, Parcet, & Miranda, 2004; Barkley, 1991; Nigg, Hinshaw, & Halperin, 1996; Olson, Schilling, & Bates, 1999), teacher ratings (Barkley, 1991; Brewis, 2002; Halperin, Sharma, Greenblatt, & Schwartz, 1991; Halperin et al., 1988; Klee & Garfinkel, 1983), clinical diagnostic interviews (Epstein et al., 2003), direct observations of impulsive behavior while completing academic assignments (Barkley, 1991), and composite indices of direct observations, parent/teacher reports, and self-report (Moffitt et al., 2011).

Examples of laboratory tasks designed to measure impulsive responding (i.e., commission errors) in children with ADHD include continuous performance tests (CPTs) and visual match-to-sample tasks. CPT variants (e.g., vigilance, *n*-back tasks) characteristically require children to respond to infrequently occurring, phonologically encoded stimuli (e.g., letters or numbers; Nichols & Waschbusch, 2004), whereas visual match-to-sample (VMTS) tasks require rapid discrimination among visuospatial stimuli (Carlson, Lahey, & Neeper, 1986; Inoue et al., 1998; Rapport et al., 1996). Impulsive responding on these tasks may reflect distinct or combined underlying executive function (EF) deficits due to cognitive processing differences associated with how task stimuli are encoded (phonologically, visuospatially), and the degree of inhibitory

control and working memory processes required by the tasks (Denney, Rapport, & Chung, 2005; Klein, Wendling, Huettner, Ruder, & Peper, 2006). To date, however, no study has investigated whether deficiencies in specific executive functions mediate ADHD-related commission errors on paradigm-specific tasks.

Executive functions involve frontal/prefrontal cortical areas that allow for the planning, regulation, execution, and inhibition of behavior (for a review, see Willcutt, Doyle, Nigg, Faraone, & Pennington, 2005). Behavioral inhibition (BI) and working memory (WM) have emerged as two of the most promising executive functions for explaining a wide array of ADHD symptoms based on recent meta-analytic reviews (Willcutt et al., 2005), empirical studies (Holmes et al., 2010), comprehensive reviews (Sergeant, Geurts, & Oosterlaan, 2002), and factor analytic results of executive functioning deficits associated with the disorder (Sonuga-Barke, Bitsakou, & Thompson, 2010). Both candidate processes are featured in contemporary models of ADHD (Barkley, 2006; Rapport, Alderson et al., 2008; Sonuga-Barke, 2002), but the models diverge significantly regarding the primacy of these processes, and the mechanisms through which these executive function deficits may result in excessive commission errors.

Behavioral inhibition (BI) is hypothesized as a cognitive process that sub-serves behavioral regulation and specific executive functions (Barkley, 2006), and underlies the ability to withhold or stop an on-going response (Schachar, Mota, Logan, Tannock, & Klim, 2000). ADHD-related excessive commission errors are hypothesized to occur by means of two interrelated pathways. The first pathway reflects a direct impact of ADHD-related deficient inhibitory processes on impulsive errors such that motor responses initiated in response to prepotent stimuli are not overridden or terminated following commands from frontal/pre-frontal cortical areas (Aman,

Roberts, & Pennington, 1998; Aron & Poldrack, 2005). The second pathway reflects indirect effects of ADHD-related deficient inhibitory processes on working memory, one of the four executive functions described by Barkley (2006) that may be affected adversely secondary to primary BI deficits. Specifically, deficient inhibitory processes fail to prevent extraneous information from entering WM, resulting in difficulty maintaining task goals and stimulus configurations due to interference (Barkley, 2006; Brocki, Randall, Bohlin, & Kerns, 2008). Finally, the excessive commission errors exhibited by children with ADHD may reflect both direct and indirect influences of BI deficiencies.

The functional working memory model of ADHD, in contrast, posits that impulsive responding on cognitive tasks (i.e., commission errors) is a byproduct of deficient working memory processes (Rapport, Kofler, Alderson, & Raiker, 2008). Working memory refers to a limited capacity system for the temporary storage, rehearsal, and manipulation of internally-held information for use in guiding behavior. Extensive evidence reveals two distinct working memory subsystems, phonological and visuospatial, that are overseen by a domain-general attentional controller termed the central executive (Baddeley, 2007). Phonological and visuospatial working memory refer to the central executive working in conjunction with the verbal and visuospatial storage/rehearsal mechanisms, respectively, to process internally-held, modality-specific information. Working memory deficits are expected to result in impulsive responding on laboratory tasks by means of three interrelated processes. The first of these processes reflects deficient storage/rehearsal capacity that may cause children with ADHD to prematurely forget task rules and instructions needed for successful performance. The second process reflects an inability to hold multiple stimuli simultaneously or for the duration necessary

to make accurate comparisons. Finally, deficient central executive processing – which is particularly impaired in children with ADHD (Kofler, Rapport, Bolden, Sarver, & Raiker, 2010) – may result in failure to effectively process and update information within working memory, or result in internal interference from task-irrelevant stimuli concurrently held within working memory (Rapport, Kofler et al., 2008).

The current study is the first to test competing predictions stemming from the BI and WM models regarding the underlying mechanisms responsible for children's impulsive responding (i.e., commission errors) on tasks used commonly in laboratory and clinical settings. For the *behavioral inhibition model*, BI processes were hypothesized to partially or fully mediate the relationship between diagnostic group membership (ADHD, typically developing children) and task-related impulsive responses on both tasks to the extent that performance on the two tasks relies on these processes for successful execution. BI processes were also expected to exert indirect effects on task-related impulsive responses to the extent that hypothesized BI deficits weaken working memory processes needed for successful task performance. In addition, any mediating effects of BI on the magnitude of between-group (ADHD, typically developing children) impulsivity differences should remain significant after removing WM influences, whereas any WM mediating effect should no longer be significant after removing BI influences.

For the *working memory model*, increased ADHD-related impulsive responding on both tasks (CPT, VMTS) was expected to be fully mediated by WM central executive processes to the extent that task performance relies on these processes for successful execution. WM central executive processes were also hypothesized to exert greater magnitude effects relative to both WM storage/rehearsal subcomponents given the larger magnitude central executive relative to

storage/rehearsal deficits associated with ADHD (e.g., Kofler et al., 2010; Rapport, Alderson et al., 2008) The hypothesized partial mediating effects of phonological and visuospatial storage/rehearsal, however, were expected to be modality specific based on the assumptions that children process letters phonologically during the CPT, and utilize their visuospatial subsystem to identify complex matching stimuli during the VMTS.

Finally, the WM model views inhibited behavior as a response to environmental events and postulates that these events require *a priori* registration and processing by WM before they can be acted upon (Rapport, Chung, Shore, & Isaacs, 2001). As a result, any mediating effects of WM on the magnitude of between-group impulsivity differences were expected to remain significant after removing BI influences. In addition, any BI mediating influences on impulsive responding should no longer be apparent after removing WM influences.

# CHAPTER 2: METHODOLOGY

## Participants

The sample consisted of 41 boys aged 8 to 12 years, recruited by or referred to a children's learning clinic (CLC) through community resources (e.g., pediatricians, community mental health clinics, school system personnel, self-referral). The CLC is a research-practitioner training clinic known to the surrounding community for conducting developmental and clinical child research and providing *pro bono* comprehensive diagnostic and psychoeducational services. Its client base consists of children with suspected learning, behavioral or emotional problems, as well as typically developing children (those without a suspected psychological disorder) whose parents agree to have them participate in developmental/clinical research studies. A psychoeducational report was provided to the parents of all participants. All parents and children gave their informed consent/assent prior to participating in the study, and approval from the university's Institutional Review Board was obtained prior to the onset of data collection. Two groups of children participated in the study: children with ADHD, and typically developing children without a psychological disorder.

## Group Assignment

All children and their parents participated in a detailed, semi-structured clinical interview using the Kiddie Schedule for Affective Disorders and Schizophrenia for School-Aged Children (K-SADS). The K-SADS assesses onset, course, duration, severity, and impairment of current and past episodes of psychopathology in children and adolescents based on DSM-IV criteria. Its psychometric properties are well established, including interrater agreement of .93 to 1.00, test-

retest reliability of .63 to 1.00, and concurrent (criterion) validity between the K-SADS and psychometrically established parent rating scales (Kaufman et al., 1997).

Twenty-one children met the following criteria and were included in the ADHD-Combined Type group: (1) an independent diagnosis by the CLC's directing clinical psychologist using DSM-IV criteria for ADHD-Combined Type based on K-SADS interview with parent and child which assesses symptom presence and severity across home and school settings; (2) parent ratings of at least 2 *SD*s above the mean on the Attention-Deficit/Hyperactivity Problems DSM-Oriented scale of the Child Behavior Checklist (CBCL; Achenbach & Rescorla, 2001), or exceeding the criterion score for the parent version of the ADHD-Combined subtype subscale of the Child Symptom Inventory-4: Parent Checklist (CSI-P; Gadow, Sprafkin, & Salisbury, 2004); and (3) teacher ratings of at least 2 *SD*s above the mean on the Attention-Deficit/Hyperactivity Problems DSM-Oriented scale of the Teacher Report Form (TRF; Achenbach & Rescorla, 2001), or exceeding the criterion score for the teacher version of the ADHD-Combined subtype subscale of the Child Symptom Inventory-4: Teacher Checklist (CSI-T; Gadow et al., 2004). The CBCL, TRF, and CSI are among the most widely used behavior rating scales for assessing psychopathology in children. Their psychometric properties are well established (Rapport, Kofler, et al., 2008). 33.3% of the children in the ADHD group were comorbid for Oppositional Defiant Disorder (ODD). None of the children were comorbid for additional DSM-IV childhood disorders.

Twenty children met the following criteria and were included in the typically developing group: (1) no evidence of any clinical disorder based on parent and child K-SADS interview; (2) normal developmental history by maternal report; (3) ratings within 1.5 *SD*s of the mean on all

CBCL and TRF scales; and (4) parent and teacher ratings within the non-clinical range on all CSI subscales. Typically developing children were recruited through contact with neighborhood and community schools, family friends of referred children, and other community resources.

Children with a history of (a) gross neurological, sensory, or motor impairment by parent report, (b) history of a seizure disorder by parent report, (c) psychosis, or (d) Full Scale IQ score less than 85 were excluded from the study. None of the children received medication during the study. Eleven had previously received psychostimulant trials or were currently prescribed psychostimulants but withheld medication for a minimum of 24 hours prior to each testing session. Demographic data for the two groups are provided in Table 1.

## Measures

### Working Memory

The phonological (PH) and visuospatial (VS) working memory tasks used in the current study are identical to those described by Rapport, Alderson and colleagues (2008). Each child was administered four phonological and four visuospatial tasks (i.e., PH and VS set sizes 3, 4, 5, and 6) across the four testing sessions. The eight working memory set size conditions each contained 24 unique trials of the same stimulus set size, and were counterbalanced across the four testing sessions to control for order effects and potential proactive interference effects across set size conditions (Conway et al., 2005). Five practice trials were administered before each task; children were required to achieve 80% correct before advancing to the full task (Rapport et al., 2008). Previous studies of ADHD and typically developing children indicate large magnitude between-group differences on these tasks (Rapport, Alderson, et al., 2008), and

performance on these tasks predict ADHD-related impairments in objectively measured activity level (Rapport et al., 2009) and attentive behavior (Kofler et al., 2010). Evidence for reliability and validity of the eight working memory tasks includes high internal consistency ($\alpha$ = .82 to .97), and demonstration of the expected magnitude of relationships (Swanson & Kim, 2007) with an established measure of short-term memory (WISC-III or -IV Digit Span raw scores: $r$ = .50 to .66). Performance data (average stimuli correct per trial) were calculated as recommended (Conway et al., 2005).

*Phonological (PH) working memory task.*

The phonological working memory task is similar to the Letter-Number Sequencing subtest on the WISC-IV (Wechsler, 2003), and assesses phonological working memory based on Baddeley's (2007) model. Children were presented a series of jumbled numbers and a capital letter on a computer monitor. Each number and letter (4 cm height) appeared on the screen for 800 ms, followed by a 200 ms interstimulus interval. The letter never appeared in the first or last position of the sequence to minimize potential primacy and recency effects, and was counterbalanced across trials to appear an equal number of times in the other serial positions (i.e., position 2, 3, 4, or 5). Children were instructed to recall the numbers in order from smallest to largest, and to say the letter last (e.g., 4 H 6 2 is correctly recalled as 2 4 6 H). Two trained research assistants, shielded from the participant's view, listened to the children's vocalizations through headphones in a separate room and recorded oral responses independently (interrater reliability was 96.2%).

*Visuospatial (VS) working memory task.*

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

Estimates of CE, PH, and VS were computed at each set size using the latent variable procedure described by Rapport, Alderson and colleagues (2008) as recommended (Swanson & Kim, 2007). Briefly, this process involved regressing the PH and VS working memory tasks onto each other, with shared variance at each set size reflecting the domain-general CE and unique variance reflecting PH and VS storage/rehearsal, respectively. Latent factors were created for each construct (CE, PH, VS) using scores at each of the four set sizes.

## Behavioral Inhibition

*Stop-signal task.*

The stop-signal task and administration instructions are identical to those described by Schachar et al. (2000). Go-stimuli were displayed for 1000 ms as uppercase letters X and O positioned in the center of a computer screen. Xs and Os appeared with equal frequency throughout the experimental blocks. Each go-stimulus was preceded by a dot (i.e., fixation point) displayed in the center of the screen for 500 ms. The fixation point served as an indicator that a

go-stimulus was about to appear. A 1000 Hz auditory tone (i.e., stop-stimulus), was delivered through sound-deadening headphones, and was generated by the computer and presented randomly on 25% of the experimental trials. Stop-signal delays (SSD)—the latency between presentation of go- and stop-stimuli—was set initially at 250 ms, and adjusted dynamically ±50 ms contingent on a participant's performance on the previous trial. Successfully inhibited stop-trials were followed by a 50 ms increase in SSD, and unsuccessfully inhibited stop-trials were followed by a 50 ms decrease in SSD. The algorithm was designed to approximate successful inhibition on 50% of the stop-trials. A two-button response box was used wherein the left button was used to respond to the letter X, and the right button was used to respond to the letter O. All participants completed two practice blocks and four consecutive experimental blocks of 32 trials (i.e., 24 go-trials, 8 stop-trials).

Stop-signal reaction time (SSRT) and Stop-signal delay (SSD) were the primary measures of behavioral inhibition in the current study. Both metrics were examined due to disagreement in the literature regarding which variable best captures the behavioral inhibition construct. For example, recent meta-analytic (Alderson, Rapport, & Kofler, 2007; Lijffijt, Kenemans, Verbaten, & van Engeland, 2005) and experimental studies (Alderson, Rapport, Sarver, & Kofler, 2008) conclude that SSD is the most valid index of behavioral inhibition in stop-signal tasks that utilize dynamic stop-signal delays, given that SSD changes systematically according to inhibitory success or failure. Other studies, however, suggest that SSRT provides a more useful indicator of behavioral inhibition (Huizenga, vans Bers, Plat, van den Wildenberg, & van der Molen, 2009; Lipszyc & Schachar, 2010). SSRT is unobservable and obtained by subtracting participants' mean SSD from mean reaction time (SSRT=MRT-SSD). Additionally,

MRT was included because previous meta-analytic reviews (Alderson et al., 2007; Lijffijt et al., 2005) and empirical studies (Alderson et al., 2008) argue that between-group SSRT differences reflect primarily MRT differences as opposed to behavioral inhibition deficits. A latent factor was composed for each BI metric (SSRT, SSD, MRT) separately to remove error and reflect reliable variance associated with each construct across the four blocks.

## Impulsivity

### *Double-letter high density continuous performance task (CPT).*

The CPT is a laboratory-based measure designed to assess children's sustained attention and impulsivity. A double-letter high target density version of the CPT was selected due to its association with high rates of both omission and commission errors (Denney et al., 2005). The task displayed a total of 540 letters one at a time at a rate of .8 s per letter with an inter-trial interval of .2 seconds between each letter. The task was comprised of three, 3-min blocks resulting in a total task completion time of approximately 9 minutes. One-hundred and eighty (33.3%) of the letters were targets (i.e., double-letters; 90 total responses) and the remaining 360 (66.7%) were non-targets. Participants were instructed to press the left mouse button every time a letter repeats itself and withhold responding to all other letters. The total number of commission errors (i.e., impulsive responding), defined as any non-target stimuli to which the participant responds, was used to compute an impulsivity score for each block. A latent factor reflecting reliable variance associated with the impulsivity construct across the three blocks served as the overall CPT impulsivity score.

*Visual match-to-sample (VMTS) task.*

The VMTS task features complex geometric visual and spatial designs and arrangements. Children were shown an abstract visual stimulus (target stimulus) surrounded by eight figures (i.e., seven nearly identical foils and one identical stimulus) and instructed to locate the one exact matching stimulus from the stimulus field as quickly as possible without making errors (see Figure 1). The figures were each 10 $cm^2$ in size and evenly spaced within a 3x3 configuration such that the total computer screen space measured 41 cm by 30.5 cm. At the beginning of each trial, children used a track ball to position a small airplane icon inside the red box in the center of the screen to ensure orientation to the target stimuli. A single click anywhere within the center box illuminated the target stimulus and eight surrounding stimuli. The target stimulus was programmed to disappear after 10 s or after the child made an incorrect response, but could be re-illuminated by clicking anywhere within the center stimulus box. An auditory tone was emitted following each correct response. A distinctly different tone followed incorrect responses. Children continued with each trial until they located the correct stimulus for each of the 20 visuospatial trials.

Impulsivity on the VMTS paradigm is reflected by both the speed with which the child responds as well as the number of commission errors the child commits. Faster speeds and higher error rates reflect greater impulsivity. Impulsivity scores were calculated separately for the first and second halves of the task based on recommendations by Salkind and Wright (1977). Specifically, the *z*-score of the average latency to first response was subtracted from the *z*-score of the total number of commission errors to provide an impulsivity score; higher values are indicative of greater impulsivity. A latent factor reflecting reliable variance associated with these

impulsivity scores on the first and second halves of the task served as an overall estimate of VMTS impulsivity.

## Measured intelligence

All children were administered the Wechsler Intelligence Scale for Children third or fourth edition to obtain an overall estimate of intellectual functioning based on each child's estimated Full Scale IQ (FSIQ; Wechsler, 2003). The changeover to the fourth edition was due to its release during the conduct of the study and to provide parents with the most up-to-date intellectual evaluation possible. The Full Scale Intelligence Quotient (FSIQ) was not analyzed as a covariate because it shares significant variance with working memory and would result in removing substantial variance associated with working memory from working memory (Ackerman, Beier, & Boyle, 2005). Instead, a residual FSIQ score was derived using a latent variable approach in which variance shared between the three working memory components (i.e., CE, PH, and VS) and FSIQ was regressed from FSIQ. The residual FSIQ score ($FSIQ_{res}$) represents IQ that is unrelated to working memory functioning and was examined to evaluate between-group differences in intellectual functioning.

## Procedures

All children participated in four consecutive Saturday assessment sessions. The phonological, visuospatial, stop-signal, CPT, and VMTS tasks were administered as part of a larger battery of laboratory-based tasks that required the child's presence for approximately 2.5 hours per session. All tasks were counterbalanced across testing sessions to minimize order effects. Children completed all tasks while seated alone in an assessment room. All children received brief (2-3

min) breaks following each task, and preset longer (10-15 min) breaks after every two to three tasks to minimize fatigue. Children were seated approximately 0.66 m from the computer monitor for all tasks.

# CHAPTER 3: RESULTS

## Preliminary Analyses

All variables were screened for univariate/multivariate outliers and tested against $p < .001$ (Tabachnick & Fidell, 2007). No significant outliers were found.

Sample ethnicity was mixed and included 26 white non-Hispanic (63%), 8 Hispanic English-speaking (20%), 2 African American (5%), and 5 children of mixed racial/ethnic background (12%). All parent and teacher behavior rating scale scores were significantly higher for the ADHD group relative to the TD group as expected (see Table 1). Children with ADHD and TD children did not differ on age ($p = .12$), SES ($p = .15$), or $FSIQ_{res}$ ($p = .81$). We therefore report simple model results with no covariates so that B-weights of key pathways can be interpreted as Cohen's *d* effect sizes (Hayes, 2009).

## Tier I: Intercorrelations

Intercorrelations between all variables were computed in Tier I of the analyses via bootstrapping (90% confidence intervals) as a first step to determine whether mediation analyses were justified. All model-specified variables were interrelated significantly with the exceptions noted below and in Table 2. Models investigating potential, but non-significant, mediating pathways (i.e., SSD mediating the diagnostic status/VMTS relationship, MRT mediating the diagnostic status/CPT relationship, and VS Storage/Rehearsal mediating the diagnostic status/VMTS relationship) were not tested because a first-order correlation is expected to exist between a potential mediating variable and the dependent variable prior to entering them into a mediating model (Baron & Kenny, 1986).

## Tier II: Mediation Analyses

All analyses were completed utilizing a bias-corrected bootstrapping procedure following the steps recommended by Shrout and Bolger (2002). Bootstrapping was used to estimate and determine the statistical significance of all total, direct, and indirect effects, and is appropriate for total sample sizes as low as 20 (Efron & Tibshirani, 1993). All continuous variables were standardized as *z*-scores to facilitate between- and within-model comparisons and allow unstandardized regression coefficients (B-weights) to be interpreted as Cohen's *d* effect sizes when predicting from a dichotomous grouping variable (Hayes, 2009). AMOS version 18.0.2 was used for all analyses, and 5,000 samples were derived from the original sample (n=41) by a process of resampling with replacement (Shrout & Bolger, 2002). Only manifest variables were included in the mediation models; therefore, all models are just-identified with perfect fit and no fit statistics are reported.

Separate mediation models were tested to examine the extent to which each of the significantly related Tier I working memory and behavioral inhibition constructs attenuated the relationship between diagnostic group and children's impulsivity scores on the CPT and VMTS. Adopting mediation analysis terminology, the *total effect* represents the relationship between diagnostic status (ADHD, TD) and children's CPT and VMTS impulsivity scores prior to examining whether hypothesized WM and BI variables serve as significant mediators of these relationships (path c in Figure 2 and Tables 3 and 4). In contrast, the *direct effects* represent the regression coefficients across models for diagnostic status (ADHD, TD) predicting WM (PH storage/rehearsal, VS storage/rehearsal, central executive) or BI (SSD, SSRT, MRT; path a in Figure 2 and Tables 3 and 4), as well as each of the WM and BI variables predicting children's

CPT and VMTS impulsivity scores (path b in Figure 2 and Tables 3 and 4). The magnitude of the pathway in which diagnostic status predicts CPT and VMTS impulsivity scores after accounting for the potential mediating influence of WM and BI variables also is considered a direct effect and reported separately (path c' in Figure 2 and Tables 3 and 4). The residual difference in effect magnitude before (c pathway) and after (c' pathway) accounting for mediating variables reflects the *indirect effect* for each of the mediating pathways (path ab in Figure 2 and Tables 3 and 4).

Effect ratios (indirect effect divided by total effect) were calculated to estimate the proportion of each significant total effect that was attributable to the mediating pathway (indirect effect). Effect ratios were not calculated for models with indirect effect confidence intervals that included 0.0. Confidence intervals containing 0.0 indicate that the magnitude of the indirect effect was not significantly different than zero, and are interpreted as no effect. Except where noted, all confidence intervals reported below were significant and did not contain 0.0. Cohen's *d* effect sizes, *SE*, 90% confidence intervals, and effect ratios are shown in Tables 3 and 4. 90% confidence intervals were selected over 95% confidence intervals because the former are more conservative for evaluating mediating effects (Shrout & Bolger, 2002)[1].

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

## Total Effects

*Diagnostic Status and Impulsivity Scores.*

Examination of the total effect (path c) for both tasks revealed that diagnostic status was related significantly to CPT ($d$ = 1.19) and VMTS impulsivity scores ($d$ = .83), indicating large-magnitude increases in CPT and VMTS impulsivity scores for children with ADHD relative to typically developing children (Tables 3 and 4).

## Phonological Storage/Rehearsal (PH)

*CPT impulsivity.*

Diagnostic status exerted a significant direct effect on PH performance (path a, $d$ = -.64), wherein an ADHD diagnosis was associated with lower PH storage/rehearsal performance. PH storage/rehearsal performance also predicted CPT impulsivity scores (path b, B = -.39). The B-weight (unstandardized regression coefficient) for path b is not interpreted as Cohen's $d$ because the predictor is continuous (Hayes, 2009).

Examination of the mediation pathway (path ab) revealed that diagnostic status exerted a significant indirect effect on CPT impulsivity scores through its impact on children's PH storage/rehearsal performance ($d$ = .25). In doing so, it reduced significantly the magnitude of ADHD-related impulsivity scores on the CPT ($d$ = 1.19 to .94) and accounted for 21% of the total effect of diagnostic status on CPT impulsivity scores (Table 3).

*VMTS impulsivity.*

PH performance also exerted a direct effect (path b, B = -.33) on VMTS impulsivity scores. Examination of the indirect effect (path ab, *d* = .21) revealed that diagnostic status exerted a significant indirect effect on VMTS impulsivity scores through its impact on PH performance. The total effect of diagnostic status on VMTS impulsivity scores (path c, *d* =.83) was reduced to *d* = .62 (path c') after accounting for the indirect effect of ADHD on VMTS impulsivity scores through PH performance. Calculation of the effect ratio revealed that the indirect effect associated with the mediating PH pathway accounted for 25% of the total effect of diagnostic status on VMTS impulsivity scores (Table 4).

## Visuospatial Storage/Rehearsal

*CPT impulsivity.*

Diagnostic status exerted a significant direct effect (path a, *d* = -1.04) on VS performance, with ADHD diagnosis associated with lower VS performance. In contrast, VS performance was neither a significant predictor of CPT impulsivity scores (path b, *ns*) nor was it a significant mediator of the relationship between diagnostic status and CPT impulsivity scores (ab, *ns*), as the direct and indirect effect confidence intervals both included 0.0 (Table 3).

*VMTS impulsivity.*

The potential impact of VS storage/rehearsal on VMTS impulsivity scores was not examined due to the non-significant correlation between these variables in the Tier I analysis.

## Central Executive (CE)

*CPT impulsivity.*

Diagnostic status exerted a direct effect (path a, *d* = -1.44) on central executive (CE) performance, with ADHD diagnosis associated with lower CE performance. CE performance also predicted CPT impulsivity scores (path b, B = -.58). Examination of the indirect (mediation) pathway revealed that diagnostic status exerted a significant indirect effect on CPT impulsivity scores through its impact on children's CE performance (path ab, *d* = .83). In doing so, it reduced the magnitude of ADHD-related deficits in CPT impulsivity scores from *d = 1.19* (path c) to *d* = .36 (path c', with the c' pathway confidence interval including 0.0) and accounted for 70% of the total effect of diagnostic status on CPT impulsivity scores (Table 3).

*VMTS impulsivity.*

CE performance did not exert a direct effect on children's VMTS impulsivity scores (Table 4 path b, *ns*).[2] Examination of the indirect effect revealed that CE performance was a significant mediator of the diagnostic status to VMTS impulsivity score relationship (path ab, *d* = .43). Additionally, CE performance reduced the initial relationship between diagnostic status and VMTS impulsivity from *d* = .83 (path c) to *d* = .40 (path c') with the c' pathway confidence interval including 0.0. The effect ratio revealed that CE performance accounted for 52% of the total effect of diagnostic status on VMTS impulsivity scores in the model (Table 4).

[2] As argued by Hayes (2009), significant *a* and *b* pathways are not prerequisites for a significant mediating indirect *ab* effect.

## Stop-signal Reaction Time (SSRT)

*CPT impulsivity.*

Diagnostic status exerted a significant direct effect (path a, $d$ = 1.20) on stop-signal reaction time (SSRT), with ADHD diagnosis associated with longer SSRTs. Additionally, SSRT exerted a significant direct effect (path b, B = .34) on CPT impulsivity scores. Examination of the indirect (mediating) pathway (path ab, $d$ = .41) revealed that SSRT was a significant mediator of ADHD-related impulsivity on the CPT, accounting for 34% of the total effect.

*VMTS impulsivity.*

Examination of the impact of SSRT on VMTS impulsivity scores revealed that neither the direct effect of SSRT on VMTS impulsivity scores (path b, *ns*) nor its inclusion as a potential mediator of the diagnostic status to VMTS impulsivity score relationship (path ab, *ns*) were significant as reflected by confidence intervals that included 0.0 (Table 4).

## Stop-signal Delay (SSD)

*CPT impulsivity.*

Diagnostic status was related significantly to SSD (path a, $d$ = -.59), wherein ADHD was associated with shorter SSDs. In contrast, neither the SSD to CPT impulsivity score direct effect (path b, *ns*) nor its inclusion as a potential mediator of the diagnostic status to CPT impulsivity score relationship (path ab, *ns*) were significant as the confidence intervals for both relationships included 0.0 (Table 3).

*VMTS impulsivity.*

The potential impact of SSD on VMTS impulsivity scores was not examined due to the non-significant correlation between these variables in the Tier I analysis.

## Mean Reaction Time (MRT)

*CPT impulsivity.*

The potential impact of MRT on CPT impulsivity scores was not examined due to the non-significant correlation between these two variables found in the Tier I analysis.

*VMTS impulsivity.*

Diagnostic status exerted a significant direct effect (path a, $d$ = .54) on mean reaction time (MRT), with ADHD diagnosis associated with longer MRTs. In contrast, neither the direct effect of MRT on VMTS impulsivity scores (path b, *ns*) nor its inclusion as a potential mediator of the diagnostic status to VMTS impulsivity score relationship (path ab, *ns*) was significant as reflected by confidence intervals that included 0.0.

## Tier III: Working Memory and Behavioral Inhibition

A final series of analyses were undertaken to test predictions from the working memory and behavioral inhibition models regarding the primacy of and interplay between the two executive functions. These mediation analyses were conducted using CPT as the dependent variable because none of the BI metrics mediated between-group differences in VMTS measured impulsivity. Specifically, both working memory variables (CE and PH storage/rehearsal) that mediated ADHD-related CPT impulsivity were regressed onto SSRT (the only BI metric that

contributed to ADHD-related CPT impulsivity) and vice versa (SSRT regressed out of CE and PH). Residual variance left in each component (i.e., CE without SSRT, SSRT without CE, PH without SSRT, and SSRT without PH) was examined as a mediator of the ADHD-CPT impulsivity relationship to determine whether it continued to attenuate ADHD-related impulsivity. After accounting for SSRT, CE continued to exert an indirect effect on ADHD-related impulsivity (ER = .14). In contrast, after accounting for CE, SSRT no longer exerted an indirect effect on ADHD-related CPT impulsivity (90% confidence interval included zero). Similarly, after accounting for PH, SSRT no longer exerted an indirect effect on ADHD-related CPT impulsivity. Likewise, PH no longer exerted an indirect effect on ADHD-related CPT impulsivity after accounting for SSRT.

Table 1. Sample and Demographic Variables

| Variable | ADHD | | Typically Developing | | |
|---|---|---|---|---|---|
| | $\bar{x}$ | *SD* | $\bar{x}$ | *SD* | *F* |
| Age | 9.30 | 1.17 | 9.93 | 1.33 | 2.59 |
| FSIQ[a] | 103.29 | 13.51 | 110.70 | 10.97 | 3.70 |
| SES | 45.93 | 11.72 | 51.10 | 11.03 | 2.11 |
| CBCL | | | | | |
| AD/HD Problems | 71.38 | 7.07 | 54.80 | 7.91 | 50.15*** |
| TRF | | | | | |
| AD/HD Problems | 66.76 | 7.97 | 54.05 | 4.84 | 37.63*** |
| CSI-Parent | | | | | |
| ADHD, Combined | 76.52 | 12.04 | 50.10 | 11.68 | 50.80*** |
| CSI-Teacher | | | | | |
| ADHD, Combined | 64.19 | 9.86 | 49.32 | 7.75 | 28.63*** |

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

*** $p \leq .001$

[a] Between-group differences in $FSIQ_{res}$ were non-significant ($p = .81$). See Measured Intelligence section for additional details regarding $FSIQ_{res}$.

Table 2. First-order correlations

| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1. | Diagnostic status | | | | | | | | | |
| 2. | PH Storage/Rehearsal | -.32* | | | | | | | | |
| 3. | VS Storage/Rehearsal | -.53* | -.30* | | | | | | | |
| 4. | Central Executive | -.73* | .61* | .57* | | | | | | |
| 5. | SSRT | .61* | -.37* | -.50* | -.73* | | | | | |
| 6. | SSD | -.30* | -.003, ns | .43* | .34* | -.46* | | | | |
| 7. | MRT | .27* | -.37, ns | -.04, ns | -.35* | .48* | .54* | | | |
| 8. | CPT impulsivity scores | .60* | -.55* | -.28* | -.71* | .58* | -.31* | .22, ns | | |
| 9. | VMTS impulsivity scores | .42* | -.43* | -.09, ns | -.45* | .31* | .01, ns | .31* | .46* | |

Note: CPT = Continuous Performance Task; MRT = Mean Reaction Time; PH = phonological; SSD = Stop-signal delay; SSRT = Stop-signal reaction time; VMTS = Visual Match-to-Sample; VS = visuospatial. * Correlation coefficient is significant based on bootstrapped 90% confidence intervals that do not include 0.0 (Shrout & Bolger, 2002). ns = nonsignificant (90% confidence interval includes 0.0).

Table 3. Mediation analyses: Impact of Diagnosis and Executive Function on CPT impulsivity scores

| Path | | Working Memory | | | | | | Behavioral Inhibition | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | PH Storage/Rehearsal | | VS Storage/Rehearsal | | Central Executive | | SSRT | | SSD | |
| | Total Effect | *d* | *(SE)* | *d* | *(SE)* | *d* | *(SE)* | *d* | *(SE)* | *d* | *(SE)* |
| c | Diagnosis → CPT impulsivity scores | 1.19* | (.25) | 1.19* | (.25) | 1.19* | (.25) | 1.19* | (.25) | 1.19* | (.25) |
| | 90% CI of Bootstrap | .82 to 1.62 | | .82 to 1.62 | | .82 to 1.62 | | .82 to 1.62 | | .82 to 1.62 | |
| | Direct Effects | | | | | | | | | | |
| a | Diagnosis → EF | -.64* | (.29) | -1.04* | (.27) | -1.44* | (.21) | 1.20* | (.25) | -.59* | (.29) |
| | 90% CI of Bootstrap | -1.13 to -.18 | | -1.45 to -.58 | | -1.78 to -1.08 | | .78 to 1.58 | | -1.06 to -.10 | |
| b | EF → CPT impulsivity scores[1] | -.39* | (.16) | .05 | (.16) | -.58* | (.20) | .34* | (.20) | -.14 | (.16) |
| | 90% CI of Bootstrap | -.60 to -.07 | | -.19 to .35 | | -.92 to -.26 | | .02 to .67 | | -.42 to .11 | |
| c' | Diagnosis → CPT impulsivity scores | .94* | (.22) | 1.24* | (.35) | .36 | (.26) | .78* | (.30) | 1.10* | (.26) |
| | 90% CI of Bootstrap | .59 to 1.33 | | .73 to 1.87 | | -.01 to .85 | | .33 to 1.31 | | .72 to 1.59 | |
| | Indirect Effects (through mediator) | | | | | | | | | | |
| ab | Diagnosis → CPT impulsivity scores | | | | | | | | | | |
| | Bootstrap Estimate | .25* | (.17) | -.05 | (.18) | .83* | (.31) | .41* | (.27) | .09 | (.12) |
| | 90% CI of Bootstrap | .03 to .61 | | -.41 to .19 | | .37 to 1.41 | | .03 to .90 | | -.03 to .37 | |
| | Effect Ratios | .21 | | -- | | .70 | | .34 | | -- | |

Note: Bias-corrected bootstrapping was used for all analyses. Paths labels reflect standard nomenclature (cf. Fritz & MacKinnon, 2007) and are depicted in Figure 2; c and c' reflect the total and direct effect of Diagnosis on CPT commission errors before and after accounting for working memory or behavioral inhibition, respectively; CPT = Continuous Performance Task; PH = phonological; SSD = Stop-signal delay; SSRT = Stop-signal reaction time; VS = visuospatial. * Effect size (or B-weight) is significant based on 90% confidence intervals that do not include 0.0 (Shrout & Bolger, 2002); [1]Values in the *d* column for path b do not reflect effect size values due to the use of two continuous variables in the calculation of the direct effect.

Table 4. Mediation analyses: Impact of Diagnosis and Executive Function on VMTS impulsivity scores

| Path | | Working Memory | | | | Behavioral Inhibition | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | PH Storage/Rehearsal | | Central Executive | | SSRT | | MRT | |
| | Total Effect | *d* | *(SE)* | *d* | *(SE)* | *d* | *(SE)* | *d* | *(SE)* |
| c | Diagnosis → VMTS impulsivity scores | .83* | (.28) | .83* | (.28) | .83* | (.28) | .83* | (.28) |
| | 90% CI of Bootstrap | .37 to 1.28 | | .37 to 1.28 | | .37 to 1.28 | | .37 to 1.28 | |
| | Direct Effects | | | | | | | | |
| a | Diagnosis → EF | -.64* | (.29) | -1.44* | (.21) | 1.20* | (.25) | .54* | (.30) |
| | 90% CI of Bootstrap | -1.13 to -.18 | | -1.78 to -1.08 | | .78 to 1.58 | | .08 to 1.06 | |
| b | EF → VMTS impulsivity scores[1] | -.33* | (.14) | -.30 | (.17) | .08 | (.16) | .21 | (.18) |
| | 90% CI of Bootstrap | -.55 to -.10 | | -.56 to .01 | | -.21 to .32 | | -.05 to .52 | |
| c' | Diagnosis → VMTS impulsivity scores | .62* | (.29) | .40 | (.36) | .74* | (.33) | .72* | (.30) |
| | 90% CI of Bootstrap | .15 to 1.10 | | -.22 to .97 | | .19 to 1.28 | | .22 to 1.21 | |
| | Indirect Effects (through mediator) | | | | | | | | |
| ab | Diagnosis → VMTS impulsivity scores | | | | | | | | |
| | Bootstrap Estimate | .21* | (.13) | .43* | (.26) | .09 | (.20) | .11 | (.10) |
| | 90% CI of Bootstrap | .05 to .47 | | .01 to .86 | | -.24 to .42 | | .00 to .34 | |
| | Effect Ratios | .25 | | .52 | | -- | | -- | |

Note: Bias-corrected bootstrapping was used for all analyses. Paths labels reflect standard nomenclature (cf. Fritz & MacKinnon, 2007) and are depicted in Figure 2; c and c' reflect the total and direct effect of Diagnosis on VMTS commission errors before and after accounting for working memory or behavioral inhibition, respectively; MRT = Mean Reaction Time; PH = phonological; SSRT = Stop-signal reaction time; VMTS = Visual Match-to-Sample; VS = visuospatial. *Effect size (or B-weight) is significant based on 90% confidence intervals that do not include 0.0 (Shrout & Bolger, 2002); [1]Values in the *d* column for path b do not reflect effect size values due to the use of two continuous variables in the calculation of the direct effect.

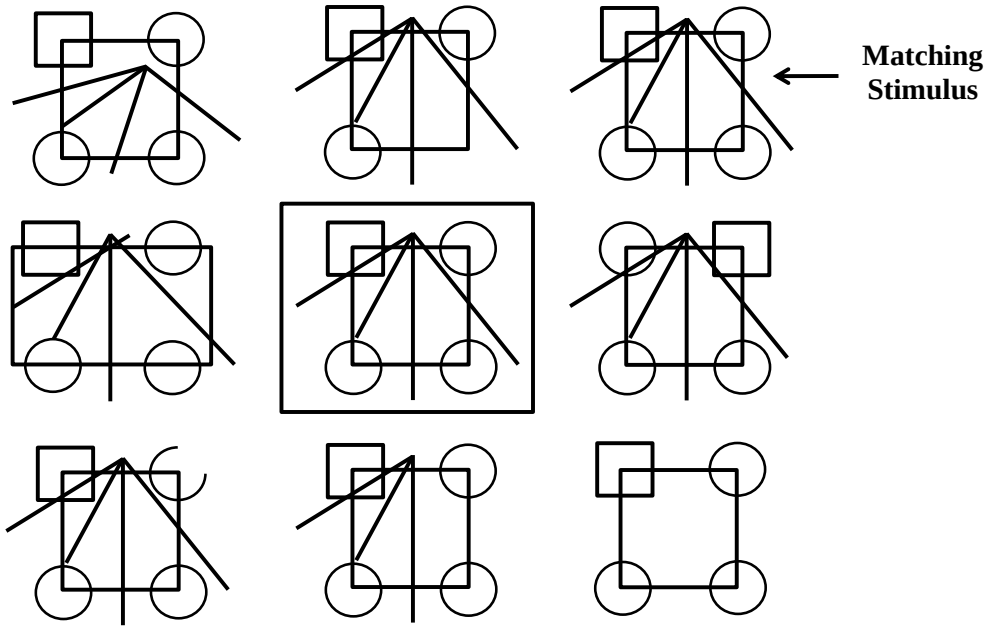



Figure 1. Visual schematic of one trial taken from the visual match-to-sample tasks (VMTS). Central picture is the target stimulus to be matched to its exact replica among 7 foils. Note: Actual size of each stimulus is 10 $cm^2$.

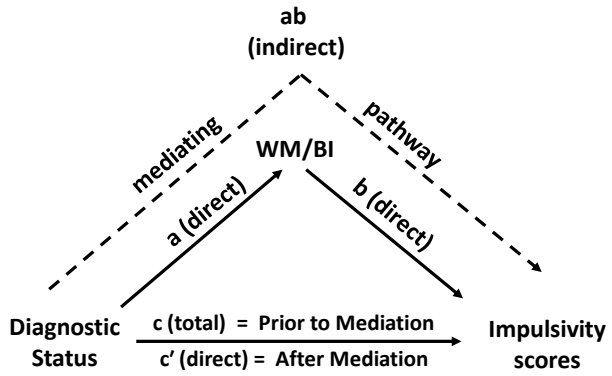



Figure 2. Visual schematic reflecting the total, direct, and indirect pathways of a bootstrapped mediation analysis before and after accounting for the mediating variable.

## CHAPTER 4: DISCUSSION

The impulsivity construct has undergone considerable scientific scrutiny over the past several decades and currently is a hallmark feature of two of the three DSM-IV ADHD subtypes (APA, 2000). Accumulating evidence indicates that the proclivity to behave impulsively falls along a continuum (Levy, Hay, McStephen, Wood, & Waldman, 1997), is influenced by genetic and environmental factors, is relatively stable throughout childhood and into adulthood, and predicts multiple adverse long-term outcomes for children with ADHD (Moffitt et al., 2010). In contrast to the plethora of information regarding longitudinal outcomes associated with impulsive behavior, the cognitive processes that may underlie ADHD-related impulsive responding have received scant empirical scrutiny. The present study addressed this imparity by testing model-driven predictions of two ADHD executive function models—behavioral inhibition (BI) and working memory (WM)—to determine the extent to which cognitive processes associated with these executive functions mediate the relationship between ADHD status and children's performance on two diverse clinical measures used to assess impulsive responding in an objective manner.

The results were highly consistent with previous investigations demonstrating large magnitude increases in impulsive responding for children with ADHD relative to typically developing children (Cohen's *d* ES = 0.83 to 1.19 across tasks). In addition, results revealed that the central executive and phonological storage/rehearsal components of working memory accounted for large and moderate proportions, respectively, of increased ADHD-related impulsivity across tasks. In contrast, visuospatial storage/rehearsal, SSD, and MRT failed to explain between-group differences on either impulsivity task, whereas SSRT partially attenuated

between-group impulsivity differences on the CPT but not VMTS. The implications of these findings are discussed below.

Collectively, the PH storage/rehearsal subsystem significantly attenuated the magnitude of ADHD-related CPT and VMTS impulsivity, accounting for 21% to 25% of group differences. These findings are consistent with oft-replicated small-to-moderate PH storage/rehearsal deficits in children with ADHD (Martinussen, Hayden, Hogg-Johnson, & Tannock, 2005), and suggest that children with ADHD would show smaller magnitude impairments on these common impulsivity paradigms if not for their phonological storage/rehearsal deficits (Rapport, Alderson et al., 2008). The involvement of PH rather than VS storage/rehearsal suggests that the VMTS paradigm's visual stimuli may be too complex to hold in the limited capacity VS storage/rehearsal subsystem for a sufficient duration to conduct a successful search involving sequential evaluation of several visually complex foils. Instead, children appear to rely on the PH subsystem to guide their search by covertly or overtly verbalizing comparative details (e.g., 'this shape's two lines at the bottom are not touching'); a supposition supported by children's anecdotal reports when asked to describe how they located the matching target figure. Overall, this interpretation is consistent with developmental research indicating that children in Western cultures demonstrate increasing reliance on their phonological relative to their visuospatial system for recalling and processing visual information as they mature (Palmer, 2000; Pickering, 2001).

The central executive (CE) component of working memory was associated with large magnitude decreases in ADHD-related impulsive responding, such that between-group impulsivity differences on the CPT and VMTS paradigms were no longer detectable after

accounting for CE functioning (i.e., both 90% ES confidence intervals included 0.0). In addition, CE functioning continued to attenuate between-group impulsivity differences after accounting for the model-implied influence of SSRT behavioral inhibition. The significant and larger contribution of the CE relative to all other tested executive functions likely reflects the involvement of several processes. For example, both the CPT and VMTS require children to focus attention and maintain relevant stimuli in a highly activated state, monitor ongoing performance, and update memory representations with the presentation of each new stimulus (Shipstead, Redick, & Engle, 2010). The large magnitude CE contributions are also consistent with a recent study reporting greater CE relative to subsystem involvement on tasks requiring working memory (Tillman, Eninger, Forssman, & Bohlin, 2011), and suggests that CE functioning plays a critical role in ADHD-related deficits on tasks traditionally interpreted as measures of impulsivity (Rapport et al., 2001). This pattern of results adds to converging evidence implicating CE impairments in ADHD-related core behavioral symptoms including inattention (Kofler et al., 2010; Burgess et al., 2010) and hyperactivity (Rapport, Bolden et al., 2009), as well as studies implicating CE deficits in ADHD-related functional impairments such as peer relationships (Kofler et al., 2011) and time estimation difficulties (Forman, Mäntylä, & Carelli, 2011).

None of the potential behavioral inhibition indices (i.e., SSRT, SSD, and MRT) were robust predictors of ADHD-related impulsive responding across both tasks. Specifically, SSD and MRT failed to mediate between-group impulsivity differences on either task, whereas SSRT partially attenuated ADHD-related impulsive responding on the CPT but not VMTS task. In addition, SSRT no longer predicted between-group CPT impulsivity differences after accounting for its

shared variance with CE or the PH storage/rehearsal subsystem. This pattern of results was surprising given that BI and impulsivity were both highly related to diagnostic status. The failure of BI to robustly mediate ADHD-related impulsive responding across tasks suggests that BI and impulsivity are both deficient in children with ADHD, but that deficient BI processes cannot fully account for their impulsive responding.

The results of the present study are consistent with past experimental investigations (Hooks, Milich, & Lorch, 1994; Inoue et al., 1998; Nigg, Hinshaw, & Halperin, 1996) and meta-analytic reviews (Frazier, Demaree, & Youngstrom, 2004; Losier, McGrath, & Klein, 1996) reporting higher rates of impulsive responding on laboratory-based paradigms in children with ADHD relative to typically developing children. Our findings, however, are inconsistent with studies reporting nonsignificant relationships between impulsivity and working memory (Brocki, Eninger, Thorell, & Bohlin, 2010; Lee, Riccio, & Hynd, 2004; Martinussen & Tannock, 2006; Thorell, 2007). This discrepancy may reflect fundamental differences in the measurement of WM and impulsivity across studies. For example, previous investigations relied on subjective parent and teacher ratings of hyperactivity/impulsivity, as opposed to the more objective laboratory-based impulsivity paradigms used in the current study. The feasibility of this explanation was examined *post hoc* by calculating correlations between parent/teacher ratings of hyperactivity/impulsivity[3] and working memory (PH storage/rehearsal, central executive). The resulting moderate-to-strong correlations between teacher/parent ratings of hyperactivity/impulsivity and WM indices ($r$ = -.46 to -.59) rendered this explanation unlikely. A more likely explanation involves the measurement of working memory. Specifically, previous

[3]The hyperactivity/impulsivity items from the ADHD subscale on the CSI were used and include hyperactivity/impulsivity DSM-IV symptom items similar to those used in the cited studies above.

studies have relied primarily on digit/location span tasks (forwards and backwards) to estimate working memory; however, converging experimental evidence reveals that both tasks are measures of short-term memory rather than working memory (Colom, Abad, Rebollo, & Shih, 2005; Rosen & Engle, 1997; Swanson & Kim, 2007), and likely underestimate the significant role of the central executive in impulsive behavior.

Results of the final series of analyses revealed that SSRT-measured behavioral inhibition was no longer significantly associated with ADHD-related impulsive responding on the CPT, whereas CE-related working memory processes continued to attenuate between-group differences after accounting for SSRT. This pattern of results, combined with initial findings that CE functioning attenuated and BI failed to attenuate between-group VMTS impulsivity differences, appears to support the WM model prediction that working memory deficits are upstream of BI (Alderson, Rapport, Hudec, Sarver, & Kofler, 2010; Rapport et al., 2001; Rapport, Kofler, et al., 2008), and contradict BI model predictions that WM deficits are a byproduct of impaired BI processes (Barkley, 1997; Barkley, 2006). A more likely explanation, however, is that the high percentage of shared variance ($R^2$ = .53) between these correlated but dissociable executive functions (Garon, Bryson, & Smith, 2008) reflects shared processes common to these and other executive functioning tasks. Although the large magnitude $R^2$ may have been related partially to our latent method of removing error variance, converging evidence indicates that WM demands reflect a primary feature of complex BI tasks such as the stop-signal used in the current study, and that the CE attentional controller may reflect a higher-order supervisory process common to all executive functions (Garon et al., 2008). Several caveats warrant consideration when considering the impact of executive functioning deficits, and

particularly deficient central executive processes, on impulsive responding by children with ADHD. Independent replication with larger samples that include females, older children, and other ADHD subtypes is needed to address the degree to which our results generalize to the larger ADHD population. Our cell sizes, however, were sufficient based on recommendations in the literature (Efron & Tibshirani, 1993; Hsu, 1989). It will also be important to examine the extent to which deficient WM processes contribute to other tasks and activities in which decision-making plays an important role, particularly those associated with adverse ADHD-related outcomes such as deficient school work and test scores (Zentall, 1993), increased risk for automobile accidents (Barkley, 2004), and employment-related difficulties (Barkley et al., 2006). Finally, several children with ADHD participating in the study were comorbid for ODD, however, the comorbidity rate was typical of the ADHD population based on epidemiological findings (i.e., 59%; Wilens et al., 2002).

The DSM-IV specified core behavioral triad—inattention, hyperactivity, and impulsivity—is associated with multiple near-, intermediate, and long-term adverse outcomes for children with ADHD (APA, 2000). Recent evidence indicates that all three symptom clusters may reflect the phenotypic expression of deficits in higher-order processes common to specific executive functions including working memory and complex behavioral inhibition (Kofler et al., 2010; Sonuga-Barke et al., 2010; Rapport et al., 2009). If correct, core behavioral symptoms and associated functional impairments of ADHD would be expected to vary according to the environmental (including cognitive) demands placed on the hypothesized substrates (Rapport et al., 2001), and improve to the extent these shared higher-order processes are susceptible to intervention. Nascent efforts aimed at increasing working memory functioning in children with

ADHD are promising and associated with small (Holmes, Gathercole, & Dunning, 2009) to medium near-term effects (Klingberg et al., 2005) on untrained tasks. These interventions, however, target primarily short-term storage capacity (Gibson, Gondoli, Files, Dobrzenski, & Unsworth, 2010), with only incidental training of the higher-order central executive processing deficits identified in the current study. Cognitive training approaches may need to adopt active components that place greater demands on higher-order central executive processes in future investigations to determine whether they are susceptible to training and remediation and result in greater magnitude and broader treatment effects.

## APPENDIX: IRB APPROVAL LETTER

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

# Approval of Human Research

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

To: **Mark D. Rapport** and Co-PI: **Valerie K. Sims**

Date: **February 23, 2010**

Dear Researcher:

On 2/23/2010, the IRB approved the following human participant research until 2/22/2011 inclusive:

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

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

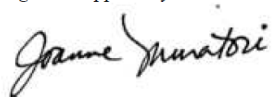
If continuing review approval is not granted before the expiration date of 2/22/2011, approval of this research expires on that date. When you have completed your research, please submit a Study Closure request in iRIS so that IRB records will be accurate.

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

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

On behalf of Joseph Bielitzki, DVM, UCF IRB Chair, this letter is signed by:

Signature applied by Joanne Muratori on 02/23/2010 10:22:55 AM EST



IRB Coordinator

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