VISUOSPATIAL WORKING MEMORY IN ADHD:
CHARACTERIZING MECHANISMS OF IMPAIRMENT

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VISUOSPATIAL WORKING MEMORY IN ADHD: CHARACTERIZING MECHANISMS OF IMPAIRMENT

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Abstract: Meta-analytic reviews provide evidence of moderate to large magnitude deficits in the visuospatial working memory (WM) of children with attention-deficit/hyperactivity disorder (ADHD), relative to typically-developing children (Kasper et al., 2012; Martinussen, Hayden, Hogg-Johnson, & Tannock, 2005; Willcutt, Doyle, Nigg, Faraone, & Pennington, 2005). The majority of studies that have researched serial visuospatial WM in ADHD have examined general performance characteristics such as span length, number of correct trials, and average stimuli correct (Kasper et al., 2012). However, relatively few studies have examined potential cognitive processes that may underlie visuospatial WM deficits (e.g., Cornoldi et al., 2001; Re, De Franchis, & Cornoldi, 2010), despite evidence from cognitive-experimental studies (Kemps, 1999; Pearson & Sahraie, 2003; Smyth, Pearson, & Pendleton, 1988) indicating that variation in visuospatial WM performance may vary as a function of how information is presented and rehearsed. More recent studies of potential determinants of WM performance have employed spatial span tasks and focused on the mentally-imaged (Kosslyn, 1994) representation of the path formed by task stimuli connected in sequence (Guérard & Tremblay, 2012; Imbo, Szmalec, & Vandierendonck, 2009; Kemps, 2001; Parmentier, Elford, & Mayberry, 2005; Parmentier & Andrés, 2006; Parmentier, Andrés, Elford, & Jones, 2006). The current study is the first to examine the effect of such path characteristics on performance in children with ADHD and typically-developing children. Both groups of children exhibited decreased performance with longer path length, consistent with hypotheses. Disproportionate effects of path crossings on performance for children in the ADHD group were observed. The findings from this study provide first-step evidence that path characteristics inform processes underlying ADHD-related WM impairment and emphasizes the need for additional research.

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CHAPTER I

INTRODUCTION

Etiological models of attention-deficit/hyperactivity disorder (ADHD) have long emphasized the role of executive function deficits (Barkley, 1997; Karalunas et al., 2017), such that the most recent revision of the DSM-5 includes ADHD with other neurodevelopmental disorders (APA, 2013). Working memory (WM) impairments have garnered particular attention as commonly associated neurocognitive deficits (Halperin, Trampush, Miller, Marks, & Newcorn, 2008), candidate endophenotypes (Castellanos & Tannock, 2002), executive deficits downstream of disinhibition (Barkley, 1997), or a central core deficit (Rapport et al., 2008) of ADHD. WM allows for temporary information storage, maintenance, and manipulation (Atkinson & Shiffin, 1968) of task-relevant information needed for goal-directed behavior (Miller & Cohen, 2001). Baddeley's multicomponent WM model (Baddeley & Hitch, 1974; Baddeley, 2007, 2012) is the most commonly investigated WM model in cognitive literature (Colette & Van der Linden, 2002) and the most commonly referenced WM model in ADHD research (Kasper, Alderson, & Hudec, 2012). The model specifies domain-specific storage and rehearsal mechanisms (the phonological buffer/loop and the visuospatial sketchpad; Baddeley, 2007), which are directed by a domain-general central executive (CE; Ang & Lee, 2008; Baddeley, 20212) that manages controlled-focused attention, allocates resources to subsidiary systems, coordinates strategic use of subsidiary systems, maintains mental representations robust to interfering stimuli, monitors information, updates representations as needed, and manipulates stored information (Baddeley, 2007).

The presence of ADHD-related WM deficits has been extensively documented. The most recent meta-analytic review of ADHD-related WM impairments (Kasper et al., 2012) reported moderate-magnitude between-group effect sizes associated with both phonological (PH) and visuospatial (VS) task performance (Hedge's $g = 0.69$ and $g = 0.74$, respectively). Notably, a best-case estimate procedure was used to solve meta-analytic regression equations reported in the review with moderator values associated with best practice procedures (e.g., comprehensive diagnostic assessments vs. single raters; greater trials numbers; high CE demands). Findings from the procedure revealed that approximately 98% of children with ADHD are expected to exhibit WM performance below the average performance of neurotypical peers, with the greatest deficits being associated with the VS system (Kasper et al, 2012).

Specific examinations of ADHD-related VS-WM deficits have yielded an extensive body of literature that includes examinations of spatial recognition (Barnett, Maruff, & Vance, 2009), spatial serial recognition (Van Ewijk et al, 2014), recall of a simultaneous array of spatial locations (Kibby & Cohen, 2008), spatial serial recall (Sowerby, Seal, & Tripp, 2011; Yang et al., 2007), spatial serial recall and manipulation (Rapport et al., 2008; Alderson et al., 2015), and visual memory (Barnett et al. 2009; Rhodes, Coghill, & Matthews, 2004) processes. Collectively, ADHD-related WM impairment has been shown with respect to initial encoding of VS stimuli (Barnett et al., 2009), the amount of items that can be stored in VS-WM (i.e., the *capacity* of the visuospatial sketchpad; Dovis, Van der Oord, Wiers, & Prins, 2013), the efficiency of rehearsal and maintenance in VS-WM (Narimoto, Matsuura, & Hiratani, 2018), and manipulation of items within WM (Brocki, Eninger, Thorell, & Bohlin, 2010). Moreover, a growing body of research has statistically isolated VS-WM and CE processes (Alderson, Rapport, Hudec, Sarver, & Kofler, 2010; Alderson et al., 2015; Raiker, Rapport, Kofler, & Sarver, 2012; Rapport et al., 2008), and extant findings indicate a potential role of interference control, rather than a general failure to attend to task stimuli (Cornoldi et al., 2001; Re, de Franchis, & Cornoldi, 2010). More complex investigations of previously unexamined mechanisms of VS-WM impairment are needed, however, to comprehensively explicate processes that may underlie ADHD-related WM deficits.

Findings from basic cognitive research suggest that VS-WM is a complex system with distinct visual and spatial memory systems (Darling et al., 2006; Klaeur & Zhao, 2004; Wager & Smith, 2003), as well as distinct processes responsible for maintaining static and sequential VS information (Della Sala et al., 1999; Hamilton et al., 2003; Pickering et al., 2001). Moreover, VS temporary memory relies on executive processes, although it is separate from the CE (Ang & Lee, 2008; Logie & Salway, 1990). Importantly, mental processes associated with movement planning, but not execution, overlap with mental processes responsible for VS task performance (Farmer et al., 1986; Logie & Salway, 1990; Quinn, 1994; Smyth & Sholey, 1994). This overlap implies a critical role of motor movement and motor movement sequences in VS-WM. For example, mental paths can be formed during completion of tasks that require memory of spatial serial order by mentally holding a visual representation of connections between successive stimuli locations in WM (Kosslyn, 1994; Parmentier et al., 2005). These paths may help to maintain stimuli in WM, either by a static mental representation of the paths that connect the stimuli in serial order, or via dynamic spatial rehearsal (in which subjects scan their visual image; Logie & Marchetti, 1991). In other words, VS tasks that require retention of serial order may elicit variability in individual rehearsal strategies.

One possible strategy involves rehearsal of a static image of the path (a static mental representation of spatial serial order stimuli), such that serial order information is maintained in a static, object-like manner (i.e., the gestalt), provided that the participant can refresh in mental imagery the overall shape of the to-be-remembered path and its starting point (see Figure 1). An alternative strategy is to rehearse the paths between stimuli in a dynamic manner, so that the movement path is maintained in mind through a dynamic internal representation (see Figure 2).

Experimental investigations of to-be-remembered path characteristics (Busch, Farrell, Lisdahl-Medina, & Krikorian, 2005; Guérard & Tremblay, 2012; Imbo, Szmalec, & Vandierendonck, 2009; Orsini, Pasquadibisceglie, Picone, & Tortora, 2001; Parmentier, Andrés, Elford, & Jones, 2006; Parmentier, Elford, & Mayberry, 2005; Pohl & Schumman-Hengsteler, 1996, as cited in Schumman-Hengsteler et al., 2004; Rossi-Arnaud, Pieroni, & Baddeley, 2006) have established the importance of set size (the number of stimuli to be recalled), path length (the successive distance between stimuli, in the correct serial order), path symmetry, and path crossings (instances in which the path formed by successive locations crosses itself, forming a non-continuous path; Imbo et al., 2009; Parmentier et al., 2005). Specifically, performance declines with increasing set sizes in healthy adults (Busch et al., 2005; Orsini et al., 2001), except during trials with a high number of path crossings (Orsini et al., 2001). Longer path lengths are associated with decreased performance in healthy adults (Guérard & Tremblay, 2012; Parmentier et al., 2005; Parmentier et al., 2006, Experiment 2) and children (Schumman-Hengsteler & Pohl, 1996). Similarly, path crossings are associated with decreased performance in healthy adults (Bor et al.; 2003 Kemps, 2001; Parmentier et al., 2005; Parmentier & Andrés, 2006) and youth (Imbo et al., 2009; Schumman-Hengsteler & Pohl, 1996).

The relationship between set size and path characteristics has not been fully characterized. Kemps (2001), for instance, found that the discrepancy in performance for structured (e.g., paths with either symmetry, repetition, and/or continuity (no crossings)) versus unstructured paths was larger when set sizes were greater, suggesting a possible interaction between path characteristics and set size, while Imbo et al. (2009) found that only set size predicted performance when simultaneously entered into a regression equation with path crossings and path length variables.

The path characteristics reviewed herein are not incompatible with Baddeley's (2012) multicomponent WM model. Specifically, crossings likely affect performance by increasing CE-related demands of interference control. That is, greater numbers of crossings increase the likelihood that target stimuli will be spatially close to other stimuli, which may interfere with correct detection/recognition. Encoding or rehearsal of each successive path segment may additionally interfere with the encoding and/or rehearsal of other path segments (see Figure 3). Crossings therefore are expected to interfere with the mental representation of a static image (which relies more on object, rather than location or order memory; Cornoldi & Vecchi, 2003). In such a case, sequential rehearsal would be needed for correct recall (see Figure 4).

Surprisingly, the effect of path characteristics has not been examined in ADHD research, despite the preponderance of findings from VS serial order tasks published in the ADHD literature (Kasper et al., 2012). The current study extends the few examinations of path characteristics in TD children and is the first to examine path length and path crossings in children with ADHD. Tier 1 of analyses examined the effect of group (TD or ADHD) and set size on VS-WM performance, using task trials with varying path lengths and crossings. A significant interaction between group and set size was expected based on previous research identifying a significant group by set size interaction (Rapport et al., 2008). Tier 2 of analyses examined the effect of group and path length (short versus medium, and medium versus long) on VS-WM performance estimated from VS-WM task trials that did not contain path crossings (to provide a methodological control for the covariance between path length and crossings, per Parmentier et al., 2005), during task set sizes of 3, 4, 5, and 6 stimuli. The ADHD group was expected to evince disproportionately worse performance during conditions with longer path length, based on previous path-length research in neurotypical adults (Parmentier et al., 2005) and children (Schumann-Hengsteler & Pohl, 1996), and the moderate to large magnitude VS-WM impairments reliably observed in children with ADHD (Kasper et al., 2012). Tier 3 of analyses examined the effect of group and path crossings (either zero or one path crossing), during set sizes of 4, 5, and 6 stimuli, on VS-WM task performance. Both groups of children were expected to exhibit worse performance during conditions with crossings, based on findings from previous research that indicate greater numbers of path crossings are associated with decreased performance on sequential spatial recall tasks (Parmentier et al., 2005, 2006). Greater numbers of path crossings were expected to disproportionately decrease performance of children with ADHD, compared to TD children, based on extant findings of exceptionally large-magnitude impairments associated with CE functioning in children with ADHD (Alderson et al., 2010; Dovis, Van der Oord, Wiers, & Prins, 2013; Rapport et al., 2008) and the probable relationship between greater numbers of crossings and greater CE demands. Finally, Tier 4 of analyses compared the magnitude of the group by path length interaction effect across set sizes 3, 4, 5, and 6, and the magnitude of the group by path crossings interaction effect across set sizes 4, 5, and 6. The magnitude of the interactions was expected to increase as a function of set size, due to the increased visuospatial sketchpad storage demands associated with greater numbers of stimuli to recall.

CHAPTER II

METHOD

Participants

Participants were typically developing (TD) children and children with ADHD aged 8-12 years, recruited from the community via fliers in local businesses, word of mouth, and through a university-based mental health clinic. Parental consent and child assent were obtained prior to participation, and the Institutional Review Board (IRB) approved the study prior to data collection. Children were assigned to either the TD or ADHD group based on the results of an evaluation that consisted of well-established, reliable, and valid behavior rating scales completed by parents and teachers, cognitive and achievement testing, clinical interviews, behavioral observations, and self-report measures. Results from cognitive testing, academic achievement testing, and clinical interviews were used to assist with diagnostic clarification and differential diagnosis. Parents of participating children were provided with comprehensive psychoeducational reports from the child's evaluation.

Forty-three children were included in the ADHD group (26% ADHD-I; 74 % ADHD-C) based on the following criteria: a diagnosis by the directing clinical psychologist based on DSM-5 (APA, 2013) criteria for an ADHD diagnosis, on the basis of a semi-structured clinical interview with children's parent(s), behavior ratings provided by parents and teachers, intellectual testing, and academic achievement testing. Specifically, participants in the ADHD group had (1) 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 (Conners, 2008) or at least 2 standard deviations greater than the mean on the DSM-oriented ADHD scales of the Conners-3P (Conners, 2008) or at least 2 standard deviations greater than the mean on the ADHD scales of the CBCL (Achenbach, & Rescorla, 2001), and (2) 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 (Conners, 2008) or at least 2 standard deviations greater than the mean on the ADHD scales of the TRF (Achenbach, & Rescorla, 2001). Given the high level of comorbidity with ADHD diagnoses (Wilens et al., 2002), children with ADHD and comborbid disorders were not excluded. The majority of children in the ADHD group (72%) had comorbid diagnoses: thirteen children met diagnostic criteria for oppositional defiant disorder, nine met criteria for specific learning disorder(s), five met criteria for elimination disorder(s), two met criteria for disruptive mood dysregulation disorder, two met criteria for generalized anxiety disorder, two met criteria for social anxiety disorder, one met criteria for separation anxiety disorder, one met criteria for specific phobia, one met criteria for dysthymia, one met criteria for major depressive disorder, and one met criteria for conduct disorder. The ADHD group was 81% male and 19% female. The race/ethnicity of the ADHD group was 79% Caucasian, 12% Native American, 2% Hispanic, and 7% Biracial. Children that were prescribed psychostimulant medication prior to participation were required to discontinue use of the medication 24 hours prior to research sessions.

Twenty-nine children were included in the TD group based on the following criteria: (1) no diagnosis by the directing clinical psychologist based on DSM-5 (APA, 2013) criteria, as evidenced by clinical interview, (2) a normal developmental history based on information provided by the parent during a psychosocial interview, and (3) ratings less than 1.5 standard deviations above the mean (i.e., within the normal range) on all clinical scales of the CBCL, TRF, Conners-3P, and Conners-3T. The TD group was 83% male and 17% female. The race/ethnicity of the TD group was 66% Caucasian, 7% Native American, 17% Asian, 3% Hispanic, and 7% Biracial.

Children presenting with (1) gross neurological, sensory, or motor impairment, (2) history of seizure disorder, (3) a history of brain injury, (4) psychosis, and/or a (5) a *Wechsler Intelligence Scale for Children-Fifth Edition* (WISC-V; Wechsler, 2014) FSIQ score less than 80 were ineligible for study participation.

Measures

VS-WM Task

Serial visuospatial working memory was assessed via a computerized task adapted from Rapport et al. (2008). Children used a touch-screen computer to complete the task, which was programmed using SuperLab Pro 4.0 (Cedrus, San Pedro, CA) software. The VS-WM task presents an offset grid consisting of three columns containing three boxes each (each measuring 2.85 x 2.85 cm; see Figure 5). The offset grid, unlike a standard grid, reduces the likelihood that children will use verbal encoding of location by associating locations with keys on a keypad.

Stimuli were colored dots (all black except one red) that sequentially appeared within each of the 9 boxes on the screen. 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. Each dot measured 2.22 cm in diameter and appeared for 800 ms with a 200 ms inter-stimulus interval. The red dot was never presented first or last in order to reduce the likelihood of recency or primacy effects, and its presentation order was counterbalanced between the first and last stimuli per item. The inclusion of one red dot added a manipulation demand to the task, in addition to the storage and rehearsal required to maintain the stimuli order and spatial locations.

Following each trial of stimuli presentation, a blank grid appeared for children to respond. 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 was exceeded, there was a 1,000 ms inter-trial interval. Afterward, the computer sounded an auditory "click" to indicate the presentation of a new item after an additional 1,000 ms.

Four blocks (set sizes 3, 4, 5, and 6) consisting of 24 trials each were administered, in a counter-balanced order (determined using a Latin Square design). Two practice blocks of five trials were administered prior to task administration to ensure that children understood the instructions. The practice block for set size 3 consisted of three stimuli, and the practice blocks for set sizes 4, 5, or 6 consisted of four stimuli. An 80% or higher success rate on the practice blocks was required prior to beginning the experimental trials.

The dependent variable for Tiers 1, 2, and 3 of analyses was the average stimuli recalled correctly for each set size of the VS-WM task. More specifically, the dependent variable for Tier 1 was calculated from responses to all trials included in set sizes (3, 4, 5, and 6), while the dependent variables for tiers 2 and 3 only included responses to a subset of trials, in order to isolate the effect of path length and path crossings, respectively (to provide a methodological control for the covariance between path length and crossings, per Parmentier et al., 2005). Study data was obtained from an ongoing, large-scale research project, and path length and path crossings conditions were determined post-hoc.

The tier 2 dependent variable only included responses to trials that did not contain path crossings. Conditions of short, medium, and long path length were defined to allow for comparisons across set sizes (i.e., the definition of a 'short' path length was consistent across set sizes). Consequently, the set sizes that contained only 3 or 4 stimuli (set sizes 3 and 4) only had trials with short and medium path lengths, and the set sizes with 5 or 6 stimuli (set sizes 5 and 6) only had trials with medium and long path lengths. The specific path length intervals (short: 200-500 pixels, medium: 501- 811 pixels, or long: 812- 1323 pixels) were determined on the basis of maximal similarity in interval ranges and number of task trials per condition. Previous examinations of path length have used pixel ranges of 1400-1600 pixels and 2000-2200 pixels (Parmentier et al., 2006) or 1400-1600, 1800- 2000, and 2200-2400 pixel categories (Parmentier et al., 2005).

Tier 3 analyses focused on performance for VS-WM trials within a constrained path range (i.e., 600 to 1000 px) and either zero or one path crossing. The path length range was determined to maximize similarity to previous research and to include a sufficient number of trials per crossing condition. The path range is broadly consistent with the 200 pixel range used in by the extant adult literature (Parmentier et al., 2005; Parmentier et al., 2006) and is developmentally appropriate in length. Tier 3 analyses did not include set size 3 trials since they did not include path crossings. Descriptive statistics for path crossings and path length in the VS-WM task are provided in Table 1.

Procedure

Children and parents participated in two clinical sessions consisting of clinical interviews, cognitive testing, and academic achievement testing, following the completion of rating scales by the children's parent and a classroom teacher. The VS-WM task was completed as part of a larger, ongoing research study, across three sessions lasting approximately three hours each. Scheduled breaks were taken throughout research sessions to reduce the likelihood of cognitive fatigue and/or frustration.

Data Analytic Plan

Main analyses were conducted using IBM Statistics Package for the Social Sciences, Version 24. Additional effect size calculations were performed using Comprehensive Meta-Analysis Version 3 (Borenstein, Hedges, Higgins, & Rothstein, 2014) software. Dependent variables were independently screened by group (ADHD, TD) for univariate outliers; no outliers were identified. Demographic data and descriptive statistics were next analyzed using independent samples *t*-tests and Pearson's chi squared tests. Tier 1 of analysis used a 2 x 4 mixed-model ANOVA with group and set size as factors. Tier 2 examined the effect of path length using a 2 x 2 mixed model ANOVA with group and path length condition (short versus medium for set sizes 3 and 4, medium versus long for set sizes 5 and 6) as factors. Tier 3, which examined path crossings, used a 2 x 2 mixed model ANOVA with group and path crossings condition (no crossings versus one crossing) as factors, for set sizes 4, 5, and 6. Finally, Tier 4 examined the effect sizes of interactions obtained from Tiers 2 and 3. Partial eta-squared values were treated as equivalent to R^2 (Lakens, 2013) and were compared using z-scores.

CHAPTER III

RESULTS

A priori power analyses

Overall Performance

A priori power analyses were conducted using G* Power software (v 3.1.92; Faul, Erdfelder, Lang, & Buchner, 2007) to determine the number of participants required to detect an interaction in a mixed model ANOVA examining group differences across set sizes. An effect size of $d = 0.88$ was chosen based on the average magnitude of VS-WM effect sizes in recent meta-analytic reviews (Kasper et al., 2012[1]; Martinussen et al., 2005; Willcutt et al., 2012). 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 (set sizes 3, 4, 5, and 6), 10 total participants were required to detect an interaction effect. The current study included complete VS-WM data for 68 children (28 typically developing and 40 with ADHD), indicating that it was sufficiently powered.

Path Length and Path Crossings

A priori power analyses were also used to determine the number of participants needed to detect an interaction effect for group by path length and group by path crossings. No previous

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[1] Hedge's *g* effect sizes were reported in Kasper et al. (2012) and were converted to Cohen's *d* for the power analyses.

research has examined the effect of path length and crossings between groups of children with and without ADHD; however, the large-magnitude VS-WM impairments evident in ADHD children provided some a priori basis for power analyses. Therefore, a conservative effect size corresponding to a medium magnitude effect (Cohen's $d = 0.50$) was used. Power was set to 0.80 based on Cohen's recommendations (1992). For an effect size of 0.50, $\alpha = .05$, power = 0.80, 2 groups and 4 set size conditions, 24 total participants were needed to detect an interaction. The current study included complete data for the path length and crossings conditions for 69 children (28 typically developing and 41 with ADHD), indicating that it was sufficiently powered.

Missing Data

Preliminary analysis revealed missing data for one child's Conners-3 rating scale [2] and for another child's FSIQ[3] (both children were in the TD group). Tier 1 of analyses had missing data for three children in the ADHD group and one child in the TD group. Tiers 2 and 3 of analyses both had missing data for two children in the ADHD group and one child in the TD group, for set sizes 4, 5, and 6. Sample size therefore varied between tiers of analyses. All missing performance data was due to computer error, and listwise deletion was used in all cases of missing data.

Outliers

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). No outliers were identified.

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[2] 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 instead used for the clinical evaluation. Parent and teacher ratings were in the clinical range for the both the DSM-IV Inattentive and DSM-IV Hyperactive-Impulsive scales.

[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.

Preliminary Analyses

Demographic data (age, SES, FSIQ, and race/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, $t(70) = 0.79$, $p =.434$, sex, $t(70) = -0.15$, $p =.885$, or race/ethnicity, $\chi^2(4) = 8.32$, $p = .08$, and consequently, those variables were not included as covariates. Children with ADHD had lower socioeconomic status than children in the TD group, $t(46.36) = 2.15$, $p = .037$; however, SES was not included as a covariate 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. Children in the ADHD group also had lower mean FSIQ[4] than children in the TD group, $t(44.13) = 3.04$, $p = .004$; however, FSIQ was not used as a covariate due to the strong association between working memory processes and FSIQ (Wechsler, 2003) that would likely remove variability from the primary dependent variable of the study (Dennis et al., 2009).

Unsurprisingly, children in the ADHD group had significantly higher *T* scores (all *p*s < .001) on the CBCL ADHD Problems DSM-oriented scale, $t(52.44) = -14.31$, the TRF ADHD Problems DSM-oriented scale, $t(52.37) = -11.85$, the C3-P DSM ADHD Inattention scale, $t(68.32) = -15.4$, the C3-P DSM ADHD Hyperactivity/ Impulsivity scale, $t(66.44) = -9.12$, the C3-T DSM ADHD Inattention scale, $t(67.72) = -18.67$, and the C3-T DSM ADHD Hyperactivity/ Impulsivity scale, , $t(53.34) = -7.57$. Sample characteristics are displayed in Table 2. Descriptive statistics were also calculated for the dependent variable conditions and are summarized in Table 3.

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[4] 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.

Tier I: Overall Performance Across Set Sizes

A 2 x 4 mixed model ANOVA examined the effect of group and set size on VS-WM performance. Mauchly's test of sphericity indicated that the assumption of sphericity was violated, $\chi^2(5) = 55.73$, $p < .001$. Therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = 0.63$ for the set size effect). There was a significant group by set size interaction, $F(1.9, 125.43) = 5.92$, $p < .01$, $\eta_p^2 = 0.08$ (see Figure 6 for a visual schematic of the group by set size interaction effect), such that the performance of the ADHD group was disproportionately negatively affected by set size. There were also significant main effects of group, $F(1, 66) = 17.67$, $p < .001$, $\eta_p^2 = 0.21$ and set size, $F(1.9, 125.43) = 13.96$, $p < .001$, $\eta_p^2 = 0.18$, such that children with ADHD had worse performance than TD children and that average stimuli correct increased from set size 3 to 4 ($p < .001$), was not significantly different between set size 4 and 5 ($p = .153$), and fell just below statistical significance ($p = .051$) for a decrease from set size 5 to 6 when adjusting for the effects of set size and group, respectively.

Two post hoc repeated-measures ANOVAs, one for each group, were used to examine group differences in average stimuli correct across set sizes. Mauchly's test of sphericity indicated that the assumption of sphericity was violated for both repeated measures ANOVAS, (TD group, $\chi^2(5) = 51.79$, $p < .001$; ADHD group, $\chi^2(5) = 28.03$, $p < .001$). Degrees of freedom were therefore corrected using the Greenhouse-Geisser estimate of sphericity ($\varepsilon = .53$ for the TD group main effect of set size, $\varepsilon = 0.66$ for the ADHD group main effect of set size). The effect of set size was significant for the TD group, $(1.59, 42.81) = 12.41$, $p < .001$, $\eta_p^2 = 0.32$, and the ADHD group, $F(1.98, 77.35) = 4.41$, $p <.05$, $\eta_p^2 = 0.10$.

Post hoc pairwise comparisons further characterized the effect of set size on average stimuli correct (table 4 summarizes the ANOVA and all post hoc tests). Within the TD group, average stimuli correct significantly increased from set size 3 to 4 ($p < .001$, $d = -2.86$) and set size 4 to 5 ($p < .05$, $d = -0.40$), but the average stimuli correctly recalled did not differ from set size 5 to 6 ($p = .740$, $d = 0.06$). The ADHD group exhibited a different pattern of results that was characterized by an increase in average stimuli correct from set size 3 to 4 ($p < .01$, $d = -0.52$), a plateau between set sizes 4 and 5 ($p = .823$, $d = 0.04$), and a significant decline in performance from set size 5 to set 6 ($p < .01$, $d = 0.52$, also see Figure 6).

Between-group differences at each condition were evaluated post hoc via *t*-tests. The ADHD group, compared to the TD group, recalled significantly fewer correct stimuli across all set sizes (set size 3 $t(62.82) = 5.16$, $p < .001$, 95% CI [0.24, 0.55], $d = 1.27$; set size 4 $t(61.01) = 4.19$, $p < .001$, 95% CI [0.35, 1.00] , $d = 1.03$; set size 5 $t(66) = 3.69$, $p < .001$, 95% CI [0.45, 1.52] , $d = 0.91$; set size 6 $t(66) = 3.74$, $p < .001$, 95% CI [0.57, 1.87] , $d = 0.92$).

Tier 2: Path Length

Set size 3

A 2 x 2 mixed model ANOVA examined the effect of group and path length condition on VS-WM performance at set size 3 and revealed a significant main effect of group, $F(1, 70) = 19.85$, $p < .001$, $\eta_p^2 = 0.22$, such that children in the ADHD group ($M = 2.26$, $SE = 0.06$) had significantly worse performance than children in the TD group ($M = 2.69$, $SE = 0.08$). Neither the main effect of path length nor the interaction between path length and group were significant, $F(1, 70) = 0.15$, $p = .700$, $\eta_p^2 = 0.002$ and $F(1, 70) = 0.38$, $p = .540$, $\eta_p^2 = 0.01$, respectively.

Set size 4

A 2 x 2 mixed model ANOVA examined the effect of group and path length condition on VS-WM performance at set size 4 and revealed a significant main effect of group, $F(1, 69) = 14.39$, $p < .001$, $\eta_p^2 = 0.17$, such that children in the ADHD group ($M = 2.68$, $SE = 0.11$) had significantly worse performance than children in the TD group ($M = 3.33$, $SE = 0.13$). Neither the main effect of path length nor the interaction between path length and group were significant, $F(1 , 69) = 2.21$, $p = .142$, $\eta_p^2 = 0.03$ and $F(1, 69) = 0.02$, $p = .895$, $\eta_p^2 < 0.001$, respectively.

Set size 5

A 2 x 2 mixed model ANOVA examined the effect of group and path length condition on VS-WM performance at set size 5 and indicated a significant main effect of group, $F(1, 68) = 16.66$, $p < .001$, $\eta_p^2 = 0.20$, such that children in the ADHD group ($M = 2.45$, $SE = 0.18$) had significantly worse performance than children in the TD group ($M = 3.58$, $SE = 0.21$). There was also a significant main effect of path length, $F(1, 68) = 13.82$, $p < .001$, $\eta_p^2 = 0.17$, such that both groups of children recalled fewer average stimuli correct during the long path length condition ($M = 2.82$, $SE = 0.16$) relative to the medium path length condition ($M = 3.20$, $SE = 0.14$). The interaction between group and path length condition was not significant, $F(1, 68) = 0.34$, $p = .563$, $\eta_p^2 = 0.01$

Set size 6

A 2 x 2 mixed model ANOVA examined the effect of group and path length condition on VS-WM performance at set size 6 and revealed a significant main effect of group, $F(1, 68) = 21.85$, $p < .001$, $\eta_p^2 = 0.24$., such that children in the ADHD group ($M = 2.23$, $SE = 0.23$) had significantly worse performance than children in the TD group ($M = 3.94$, $SE = 0.28$). Neither the effect of path length condition nor the interaction between path length by group were significant, $F(1, 68) = 2.41$, $p = .125$, $\eta_p^2 = 0.03$ and $F(1, 68) = 1.44$, $p = .235$, $\eta_p^2 = 0.02$, respectively.

Tier 3: Path Crossings

Set size 4

A 2 x 2 mixed model ANOVA examined the effect of group and path crossings condition on VS-WM performance at set size 4 and yielded a significant main effect of group, $F(1, 69) = 14.66$, $p < .001$, $\eta_p^2 = 0.16$, such that TD children correctly recalled significantly more stimuli than children with ADHD. The main effect of path crossings condition was not significant, $F(1, 69) = 0.90$, $p = .347$, $\eta_p^2 = 0.01$. There was a significant interaction between group and path crossing condition, $F(1, 69) = 4.16$, $p < .05$, $\eta_p^2 = 0.06$, such that the performance of children with ADHD was disproportionately negatively affected by path crossings. Figure 7(a) provides a visual schematic of the set size 4 group by path crossings interaction effect.

Two post hoc repeated-measures ANOVAs, one for each group, were used to examine differences in performance across conditions. The effect of path crossing condition was not significant for the TD group, $F(1, 28) = 1.72$, $p = .200$, $\eta_p^2 = 0.06$, or the ADHD group, $F(1, 41) = 3.69$, $p = .062$, $\eta_p^2 = 0.08$. Between-group differences at each path crossing condition were evaluated post hoc via *t*-tests. The ADHD group, compared to the TD group, recalled significantly fewer correct stimuli during the zero cross condition ($t(66.74) = 2.89$, $p < .01$, 95% CI [0.18, 0.98] , $d = 0.70$) and the one cross condition ($t(63.39) = 4.85$, $p < .001$, 95% CI [0.56, 1.35], $d = 1.17$).

Set size 5

A 2 x 2 mixed model ANOVA examined the effect of group and path crossings condition on VS-WM performance at set size 5 and revealed significant main effects of group $F(1, 68) = 15.66$, $p < .001$, $\eta_p^2 = 0.19$, and path crossings condition, $F(1, 68) = 5.20$, $p < .05$, $\eta_p^2 = 0.07$. The interaction between group and crossings condition, however, was not significant, $F(1, 68) = 1.69$, $p = .198$, $\eta_p^2 = 0.02$. Children in the ADHD group ($M = 2.69$, $SE = 0.17$) had significantly lower WM performance than the TD group ($M = 3.72$, $SE = 0.21$), and both groups of children exhibited better performance during the crossing condition ($M = 3.29$, $SE = 0.14$) relative to the no-crossing condition ($M = 3.10$, $SE = 0.14$). Figure 7 (b) provides a visual schematic of the path crossings condition effect.

Set size 6

A 2 x 2 mixed model ANOVA examined the effect of group and path crossings condition on VS-WM performance at set size 6 and yielded a significant interaction between group and path crossings, $F(1, 68) = 6.08$, $p < .05$, $\eta_p^2 = 0.08$, and a significant main effect of group, *F*(1,68) = 15.40, $p < .001$, $\eta_p^2 = 0.19$ such that children in the ADHD group had significantly worse performance than children in the TD group. The effect of path crossings condition was not significant, *F*(1, 68) = 0.84, $p = .363$, $\eta_p^2 = 0.08$. Figure 7 (c) provides a visual schematic of the group by path crossings interaction effect. Two post hoc repeated-measures ANOVAs, one for each group, were used to characterize the within-group effect of path crossings. The effect of the crossings condition was not significant for the TD group, *F*(1, 27) = 1.56, $p = .222$, $\eta_p^2 = 0.06$, but was significant for the ADHD group, *F*(1, 41) = 5.78, $p < .05$, $\eta_p^2 = 0.12$. Specifically, the ADHD group's performance during the crossing condition was higher than their performance during the no-crossing condition. Finally, between-group differences at each crossing condition were evaluated via post hoc *t*-tests. The ADHD group, compared to the TD group, recalled significantly fewer average correct stimuli in both conditions, but to a lesser extent in the crossing condition (no crossing condition, *t*(68) = 4.61, $p < .001$, 95% CI [0.93, 2.35], $d = 1.12$; in the crossing condition, *t*(68) = 2.91, $p < .01$, 95% CI [0.34, 1.84], $d = 0.71$).

Tier 4: Comparison of Interaction Effect Sizes

Comparison of Group by Path Length Interaction Effect Sizes (Tier 4a)

The partial eta squared values for the group by path length interactions were similar across set sizes, ranging from <.001 to .02. The values were not significantly different (all *p*'s > .39).

Comparison of Group by Path Crossings Interaction Effect Sizes (Tier 4b)

The partial eta squared values for the group by path crossings interactions were similar across set sizes, ranging from 0.02 to 0.08. The values were not significantly different (all *p*'s > .47).

CHAPTER IV

DISCUSSION

The current study examined the effect of path length (i.e., the successive distance between stimuli connected in the correct serial order) and path crossings (instances in which the path formed by successive locations crosses itself and is non-continuous) on VS-WM performance in children with ADHD and TD children. This is the first study to examine path characteristics in children with ADHD, and one of only a few studies examining path characteristics in TD children. Both groups of children completed a VS-WM task with multiple set sizes (i.e., number of stimuli to be recalled; 3, 4, 5, and 6), with post-hoc conditions of short, medium, and long path length, and zero or one crossing conditions.

As a first step, performance using all trials of the VS-WM task were examined as a function of set size and group (via a mixed-model ANOVA) to confirm between-group differences and to allow for comparison with previous and later published studies. Consistent with hypotheses and previous research (Alderson et al., 2015; Rapport et al., 2008), a significant group by set size interaction was found. Specifically, the TD group exhibited a pattern of higher average stimuli correctly recalled as set size increased, until their performance plateaued at set size 5. In contrast, the ADHD group exhibited an increase in the average stimuli correctly recalled from set sizes 3 to 4, a plateau between set sizes 4 and 5, and a performance decline from set sizes 5 to 6. These findings appear to suggest that, on average, the ADHD group's maximum

VS sketchpad capacity was approximately one stimulus less compared to children in the TD group (as evidenced by the highest average stimuli correct value for each group, regardless of set size, from Tier 1 of analyses). That is, the difference between the TD maximum average stimuli correct (3.61, occurred during set size 5) and the ADHD maximum average stimuli correct (2.65, occurred during set size 4) was 0.96). Further, our finding that children with ADHD recalled fewer items in set size 6 compared to set size 5 suggested that factors other than total VS sketchpad buffer size may have contributed to performance at the highest set size. One possible explanation is that the children with ADHD engaged in escape or avoidance behavior, as previous studies have suggested that children with ADHD frustrate more quickly than their TD peers (Scime & Norvilitis, 2006; Seymour, Macatee, & Chronis-Tuscano, 2016) and are relatively more likely to disengage from tasks as a function of increased WM demands (Kofler, Rapport, Bolden, Sarver, & Raiker, 2010; Tarle, Alderson, Arrington, & Roberts, 2019). Another potential explanation is that children with ADHD were more vulnerable to proactive and retroactive interference that is expected to increase in likelihood of occurrence as a function of increasing set sizes (May, Hasher, & Kane, 1999; Oberauer & Lin, 2017). Specifically, stimuli learned early in a sequence are more likely to proactively interfere with stimuli presented at the end of the sequence when the sequence is relatively long, given this is more information in a longer sequence to interfere (Blalock & McCabe, 2010; Cowan, Johnson, & Saults, 2005). Similarly, the effect of retroactive interference is expected to increase as a function of increasing set sizes, given the inherent primacy of stimuli learned at the end of a sequence, as well as competing demands on focused attention, maintenance, and manipulation of information previously encoded (Baddeley, 2007; Dosher, 1999; Hitch, Halliday, Schaafstal, & Schraagen, 1998).

The effect of path length was next examined, with short versus medium path length conditions examined at set sizes 3 and 4, and medium versus long path length conditions examined at set sizes 5 and 6. In addition to the consistent and expected significant main effect of group (i.e., children with ADHD recalled significantly fewer average stimuli correct) across all set sizes, the effect of path length was not significant except at set size 5. Specifically, the performance for both groups of children was worse in the long path length condition relative to the medium path length condition. The significant negative effect of path length on VS-WM performance observed at set size 5 is consistent with previous research with healthy adults (Guérard & Tremblay, 2012; Parmentier et al., 2005; Parmentier et al., 2006) and children (Schumann-Hengsteler & Pohl, 1996; Zolech & Schumman-Hengsteler, 2002; both cited in Schumman-Hengsteler et al., 2004) and is the first time the effect has been demonstrated in children with ADHD. Moreover, similar to findings from studies of healthy adults (Parmentier et al., 2005), this finding appears to suggest that children's rehearsal of visuospatial information is dynamic (i.e., mental rehearsal of path sequences). That is, if children used a static rehearsal strategy of mentally retaining one overall image that is continuously refreshed as a whole, the total distance between stimuli when connected in serial order would not be expected to affect performance (i.e., the total amount of stored information would not vary depending on path length; Parmentier et al., 2005; Parmentier & Andrés, 2006). Nevertheless, the inconsistent effect of path length across set sizes was surprising and warrants consideration.

One potential explanation for the inconsistent effect of path length is that there was not enough item variation between the path length conditions (i.e., the difference between short and medium, or medium and long, was not sufficiently large) to reliably detect effects across set sizes. It is noted that the current study examined archival data from a task with limited variability in path length and crossings, and conditions were created post-hoc. The negative effect of path length was perhaps only detected at set size 5 because set size 5 trials contained enough variability in path length to create sufficiently different conditions. Set sizes 3 and 4, due to their naturally shorter path length as a function of fewer stimuli to be recalled, may have lacked sufficient path length difference between conditions. In contrast, the path length conditions at set size 6 may have been sufficiently different in terms of item variation, but limited between-group variance obscured our ability to detect an effect. That is, the highest average stimuli correct value for each group from Tier 1 of analyses was 3.61 and 2.65 for the TD and ADHD groups, respectively (see Table 4), indicating that set size 6 exceeded the groups' maximum VS sketchpad capacity and allowed for minimal remaining variance in performance that might be attributable to path length. Finally, perhaps the simplest explanation for the inconsistent effect of path length is that the effect was spurious and resulted from multiple examinations across four set sizes. Notably, however, there was a descriptive trend of consistently lower performance in longer relative to shorter conditions (see Table 3 for both groups' performance across conditions), providing support for our previous explanations and/or suggesting greater power may have detected effects across all set sizes. Nevertheless, future studies are needed to provide evidence of a reliable effect.

The nonsignificant interaction of group by path length (for all set sizes), as well as the nonsignificant difference in the magnitude of interactions across set sizes, was unexpected. Although contrary to hypotheses, the non-significant interaction is interesting in the context of parsing specific WM processes that may contribute to performance. Broadly speaking, performance on the VS-WM task in the current study involved controlled-focused attention, encoding of stimuli, rehearsal and maintenance of stimuli, storage capacity (number of stimuli to be recalled), and CE-related serial reordering and interference control (Baddeley, 2007; Logie, 1995; Patt et al., 2014). Consideration of these specific processes as well as the significant effect for path length may serve to explicate the non-significant interaction. Specifically, it is unlikely that the within-group main effect of path length is attributable to variance in CE demands, as the path length condition was only significant at set size 5, and previous findings in cognitive literature have provided strong evidence that CE demands are largely independent of variance in set sizes (Baddeley, 2007; Curtis & D'Esposito, 2003; Van den Berg, Ronald, & Ma, 2018). That is, if within-group differences associated with path length variance were associated with CE processes, and CE demands did not vary across set sizes, one would expect similar effects of path length across all set sizes. It is therefore more likely that variance in path lengths affected storage/rehearsal processes by excessively taxing rehearsal processes and/or the maximum capacity of items stored in the VS sketchpad. This explanation is consistent with findings from previous studies that have parsed CE and storage/rehearsal processes and found that impaired CE functioning represents the greatest deficit in children with ADHD. Moreover, this explanation suggests that a significant interaction was not observed because manipulation of path length targeted VS-WM processes that were more similar between-groups and less likely to show impairment. If replicated, our finding of similar effects of path length on performance in neurotypical children and children with ADHD would expand on research of ADHD-related PH-WM functioning. That is, the few studies that have investigated potential mechanisms of PH-WM implicate both storage and rehearsal processes (Bolden et al., 2012; Karetekin, 2004), albeit to a greater extent for storage than rehearsal processes (Bolden et al., 2012).

The current study was the first to examine the effect of path crossings on VS-WM performance in children with ADHD. Contrary to hypotheses that path crossings would decrease performance, and that children with ADHD would be disproportionately negatively affected by crossings, the current study revealed both negative and positive effects of path crossings on performance, depending on set size. Specifically, children with ADHD were disproportionately negatively affected by path crossings during set size 4, relative to TD children. However, during set size 5, the presence of path crossings was uniformly associated with higher performance for both groups of children, and during set size 6, the performance of children with ADHD was disproportionately positively affected by the presence of path crossings, relative to TD children.

The finding that children with ADHD were disproportionately negatively affected by the presence of path crossings at set size 4 was consistent with our a priori hypothesis that was based on previous findings of impaired performance associated with more crossings in healthy adults (Bor et al.; 2003 Kemps, 2001; Parmentier et al., 2005; Parmentier & Andrés, 2006) and children (Imbo et al., 2009; Schumman-Hengsteler & Pohl, 1996, as cited in Schumman-Hengsteler et al., 2004), large-magnitude deficits reliably associated with CE functioning in children with ADHD

(Alderson et al., 2010; Dovis, Van der Oord, Wiers, & Prins, 2013; Kasper et al., 2012; Martinussen et al., 2005; Rapport et al., 2008), and CE demands associated with dynamic rehearsal of trials with path crossings (Parmentier, 2011). Viewed alone, the significant interaction effect suggests children with ADHD may be using a static rehearsal strategy (i.e., continuously refreshing the entire image of the stimuli connected in serial order) that does not capture all relevant information (namely, serial order) for a correct response to trials with path crossings. This interpretation, however, conflicts with the apparent dynamic rehearsal strategy used by both groups of children, as evidenced by findings from our examination of path lengths. Moreover, this interpretation is complicated by inverse findings at set sizes 5 and 6 (i.e., crossings associated with improved performance for both groups of children at set size 5 and disproportionately improved performance for children in the ADHD group at set size 6).

A tentative explanation for the apparent positive effect of path crossings could be that stimuli are closer together in space and path length is reduced under conditions of more path crossings, therefore shortening the visual or temporal length of dynamic mental rehearsal and facilitating performance. This explanation is unlikely, however, because the range of path lengths were controlled in this tier of analyses given the expected correlation between path length and path crossings (Parmentier et al., 2005), as well as the nonsignificant effect of path length effect observed in set sizes 3, 4, and 6. Another potential explanation is that the presence of crossings may have provided visual novelty/interest and children consequently paid more attention to trials with crossings. This explanation, however, does not explicate why both groups' performance improved at set size 5 and only the ADHD group's performance improved at set size 6. Alternatively, the apparent positive effect of path crossings may be a spurious finding; however, this interpretation is unlikely given that a positive effect was obtained at two of three set sizes. Finally, it may be that more variability in crossings, such as comparing 0, 3, and 6 crossings (e.g., Parmentier et al., 2005), or modeling the effect continuously via multilevel modeling, is necessary to elucidate the effect of path crossings in children. That is, path crossings may exert a complex, non-linear, effect on WM performance that was not fully explicated by the current study. This interpretation is in line with the non-significant differences between the group by path crossings interaction across set sizes and is considered to be the most probable.

The current study is the first to examine the effect of path length and path crossings on performance in children with ADHD. The study is not without limitations, however. The primary limitation of the current study is that the VS-WM task used was not designed to investigate path characteristics and therefore the path length and path crossings conditions were created post hoc. Accordingly, conditions were comprised of a small number of trials (on average, 7 trials per condition), which may have resulted in decreased variability between conditions so that path characteristics were not sufficiently manipulated. The number of trials per condition was also limited in order to maintain consistent definitions of 'short', 'medium' and 'long' path lengths to facilitate the comparison of effects across set sizes. An additional limitation is the low percentage of girls in the sample, which reduces the generalizability of findings to the larger population of children with ADHD. Nevertheless, this study is an important first step to examine potential mechanisms of impairment in ADHD-related VS-WM impairment. Future studies that employ a VS-WM task with greater variability in path characteristics, in addition to a more representative sample, are needed to confirm the tentative findings of the current study.

This study is the first to examine path characteristics in ADHD. Evidence of a negative effect of path length and disproportionate effects of path crossings on performance of children with ADHD was obtained under some set size conditions. The negative affect of path length on performance provides tentative preliminary evidence that VS-WM encoding and/or rehearsal processes minimally contribute to ADHD-related VS-WM impairments, as both groups of children were similarly affected by path length. The effect of path crossings, in contrast, followed a complex pattern of disproportionately worse performance for the ADHD group during set size 4, a uniform positive effect on performance for both groups of children during set size 5, and a disproportionate positive effect for the ADHD group performance during set size 6. To the extent that a negative disproportionate effect of path crossings was obtained for the ADHD group, findings may help to explain mathematics difficulties observed in children with ADHD (Benedetto-Nasho & Tannock, 2009; Tosto, Momi, Asherson, & Malki, 2015), given the association between visuospatial sketchpad capacity and math performance (Hitch & McAuley, 1991; Mayberry & Do, 2003), as well as the association between CE processes and the unique problem-solving demands of applied mathematics (Andersson, 2008; Bull, Johnston, & Roy, 1999). Nonetheless, findings from the current study do converge with previous cognitive (e.g., Kemps, 2001; Imbo et al. 2009; Parmentier et al., 2005) and clinical (e.g., Tarle et al., 2017; Wells, Kofler, Soto, Schaefer, & Sarver, 2018) research to emphasize the importance of subtle variations in task parameters on variation in performance.

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TABLES AND FIGURES

Table 1

Descriptive Statistics of Path Length and Path Crossings Conditions

	Item n	Mean	SD	Min	Max	Range
Path Length (px)						
Set size 3, Short	17	385.44	83.90	213.00	491.00	278.00
Set size 3, Medium	5	541.82	33.38	500.84	574.63	73.79
Set size 4, Short	9	457.89	16.65	429.01	487.62	58.61
Set size 4, Medium	7	670.43	78.43	563.96	796.16	232.20
Set size 5, Medium	6	668.83	124.10	517.48	803.49	286.01
Set size 5, Long	6	995.07	126.68	813.96	1161.40	347.44
Set size 6, Medium	1	-	-	810.64	810.64	-
Set size 6, Long	5	978.40	201.34	823.09	1322.01	498.92
Path Crossings						
Set size 4, No Cross	5	-	-	0	0	-
Set size 4, Cross	3	-	-	1	1	-
Set size 5, No Cross	10	-	-	0	0	-
Set size 5, Cross	8	-	-	1	1	-
Set size 6, No Cross	5	-	-	0	0	-
Set size 6, Cross	6	-	-	1	1	-

Table 2

Descriptive Statistics of Sample

	TD (*n* = 29 except as marked †)	ADHD (*n* = 43 except as marked †)		
	M (SD)	*M (SD)*	*t*	χ^2
Sample Characteristics				
Age in years	10.13 (1.40)	9.83 (1.65)	0.79	
FSIQ	111.68 (16.48) †N=28	100.79 (11.55)	3.04**	
Gender	24 boys, 5 girls (83% male)	35 boys, 8 girls (81% male)	-0.15	
Ethnicity				8.32
Caucasian	19 (66% white)	34 (79% white)		
Native American	2	5		
Asian	5	0		
Hispanic	1	1		
Biracial	2	3		
SES[a]	51.41 (13.01)	45.42 (9.15)	2.15*	
CBCL DSM-ADHD *T* score	51.17 (2.16)	67.95 (7.23)	-14.31***	
TRF DSM-ADHD *T* score	51.07 (2.14)	64.88 (7.19)	-11.85***	
C3-P ADHD-I *T* score	46.24 (7.079)	76.26 (9.33) †N=42	-15.40***	
C3-P ADHD-HI *T* score	46.86 (7.98)	71.17 (14.35) †N=42	-9.12***	
C3-T ADHD-I *T* score	44.76 (5.03)	74.76 (8.47) †N=42	-18.67***	
C3-T ADHD-HI *T* score	45.69 (5.81)	67.52 (17.34) †N=42	-7.57***	

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 3

Average Performance Across Path Length and Path Crossings Conditions

	Full Sample		TD Group		ADHD Group	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**
Path Length						
Set size 3, Short	2.44	0.40	2.69	0.23	2.28	0.40
Set size 3, Medium	2.42	0.58	2.70	0.31	2.23	0.65
Set size 4, Short	2.99	0.79	3.39	0.48	2.72	0.86
Set size 4, Medium	2.89	0.87	3.28	0.46	2.63	0.98
Set size 5, Medium	3.10	1.24	3.74	0.88	2.67	1.27
Set size 5, Long	2.70	1.40	3.42	1.26	2.23	1.29
Set size 6, Medium	3.04	2.20	4.21	1.93	2.26	2.02
Set size 6, Long	2.78	1.55	3.66	1.40	2.19	1.38
Path Crossings						
Set size 4, No Cross	2.85	0.95	3.19	0.60	2.61	1.07
Set size 4, Cross	2.72	1.02	3.29	0.54	2.33	1.10
Set size 5, No Cross	2.98	1.26	3.68	0.92	2.51	1.25
Set size 5, Cross	3.20	1.24	3.76	0.93	2.82	1.28
Set size 6, No Cross	2.94	1.66	3.93	1.37	2.29	1.52
Set size 6, Cross	3.10	1.62	3.76	1.62	2.66	1.48

Note. TD = typically developing; ADHD = attention-deficit/hyperactivity disorder.

Table 4

VS-WM Performance Across Set Sizes (Tier 1)

	M	*SE*	*F*	*t*	*d*	Post hoc
Between Group			17.67***			
Within Group			13.96***			
Group x Set Size			5.92**			
TD Post hoc Repeated Measures ANOVA			12.41***			3 < 4***, 5***, 6** 4 < 5* 4 = 6 5 = 6
ADHD Post hoc Repeated Measures ANOVA			4.41*			3 < 4**, 5* 3 = 6 4 = 5 4*, 5** > 6
Set size 3				5.16***	1.27	
TD	2.69	0.04				
ADHD	2.29	0.07				
Set Size 4				4.19***	1.03	
TD	3.33	0.08				
ADHD	2.65	0.14				
Set Size 5				3.69***	0.91	
TD	3.61	0.18				
ADHD	2.62	0.18				
Set Size 6				3.74***	0.92	
TD	3.56	0.27				
ADHD	2.33	0.20				

Note. TD = typically developing; ADHD = attention-deficit/hyperactivity disorder; *M* = estimated marginal mean; *SE* = standard error.

* $p < .05$, ** $p < .01$, ***$p < .001$

Figure 1

Gestalt of Serial Order Information

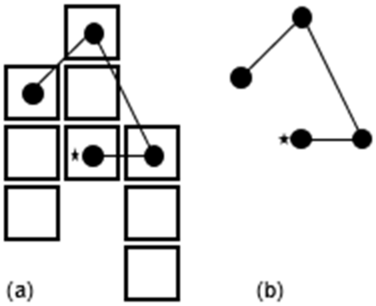


Figure 1(a) represents the path connecting stimuli that have been connected in sequence. Figure 1(b) clarifies the information to be rehearsed in the VS-WM - it is an image.

Figure 2

Dynamic Rehearsal of Serial Order Information

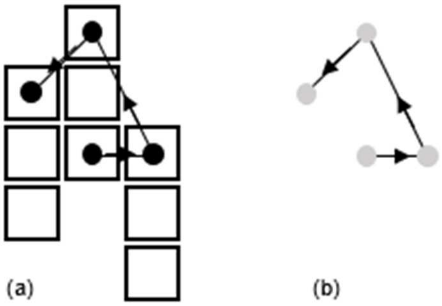
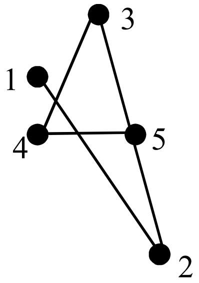


Figure 2(a) represents the path connecting stimuli that have been connected in sequence. Figure 2(b) clarifies the information to be rehearsed dynamically in VS-WM - it is a <u>movement path</u>.

Figure 3

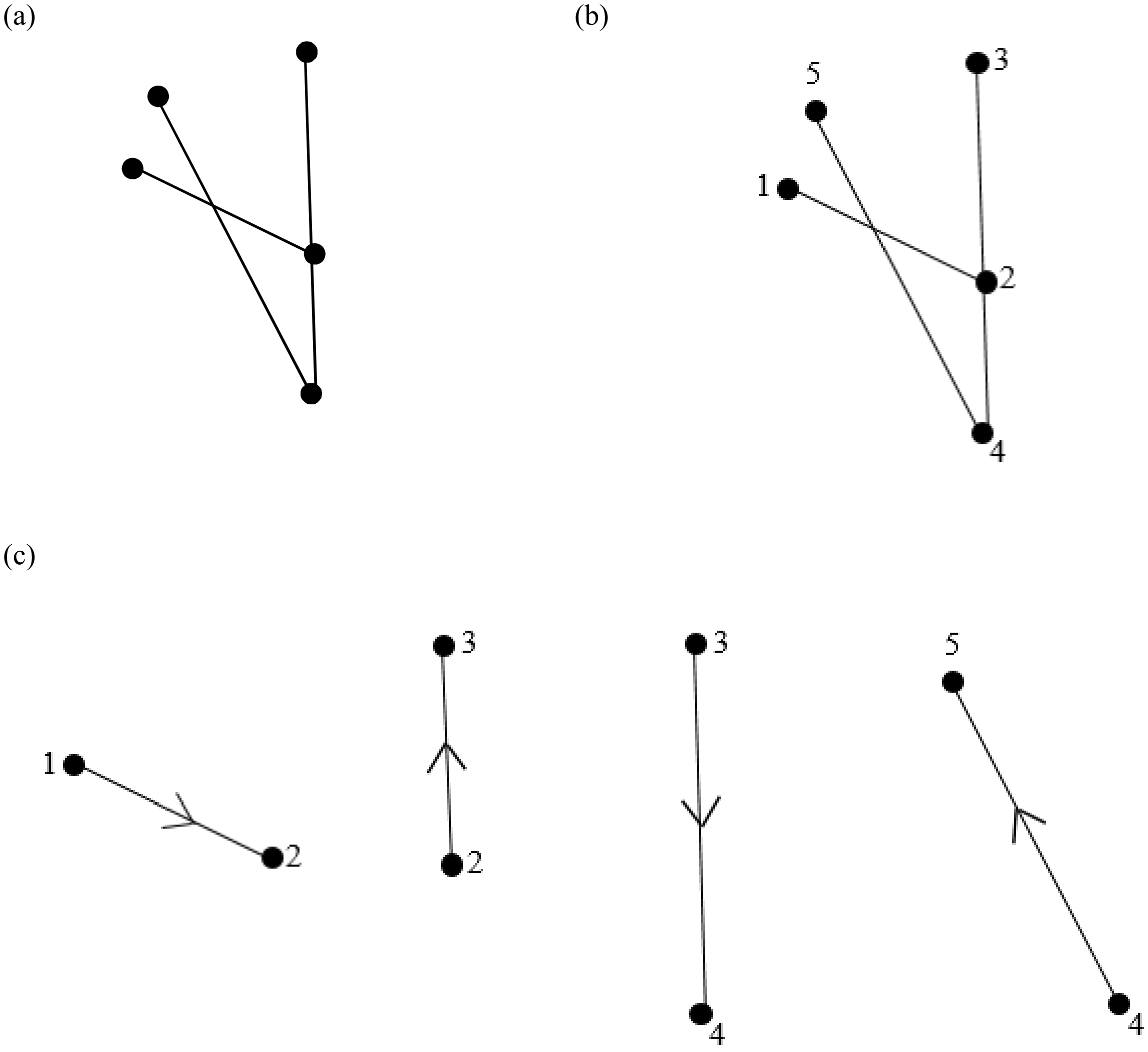
Interference in a Spatial Serial Recall Task



The path from 4 to 5 may be disrupted from path 1 to 2 (retroactive interference) or vice versa (proactive interference).

Figure 4

Interference and Sequential Rehearsal in a Spatial Serial Recall Task



The static configuration displayed in (a) does not allow for the correct serial order, depicted in (b). Each part of the sequence (e.g., the path from stimulus 1 to 2, the path from stimulus 2 to 3) is represented in (c).

Figure 5

VS-WM Task

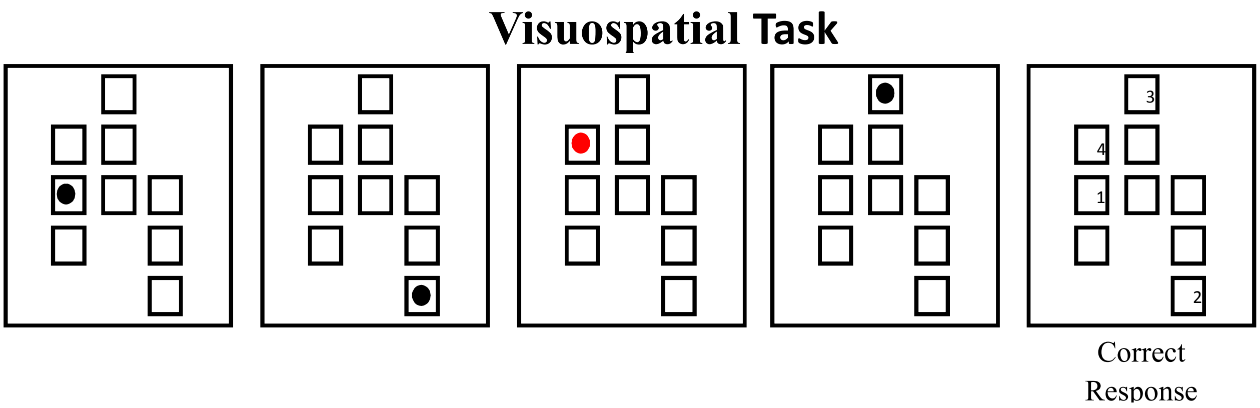
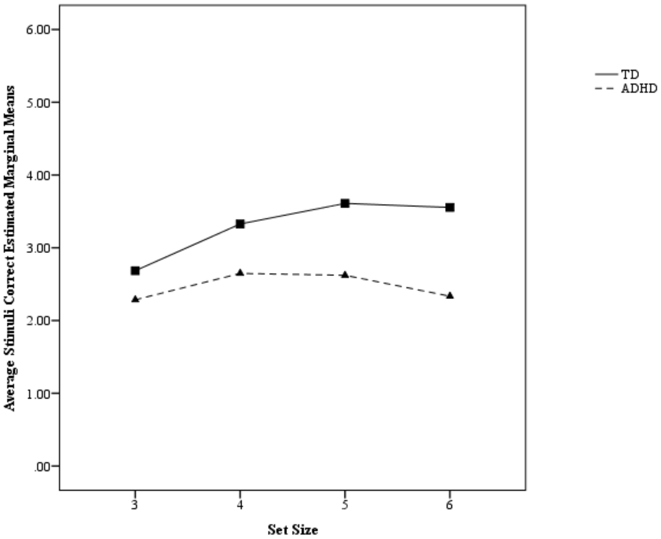


Figure 6

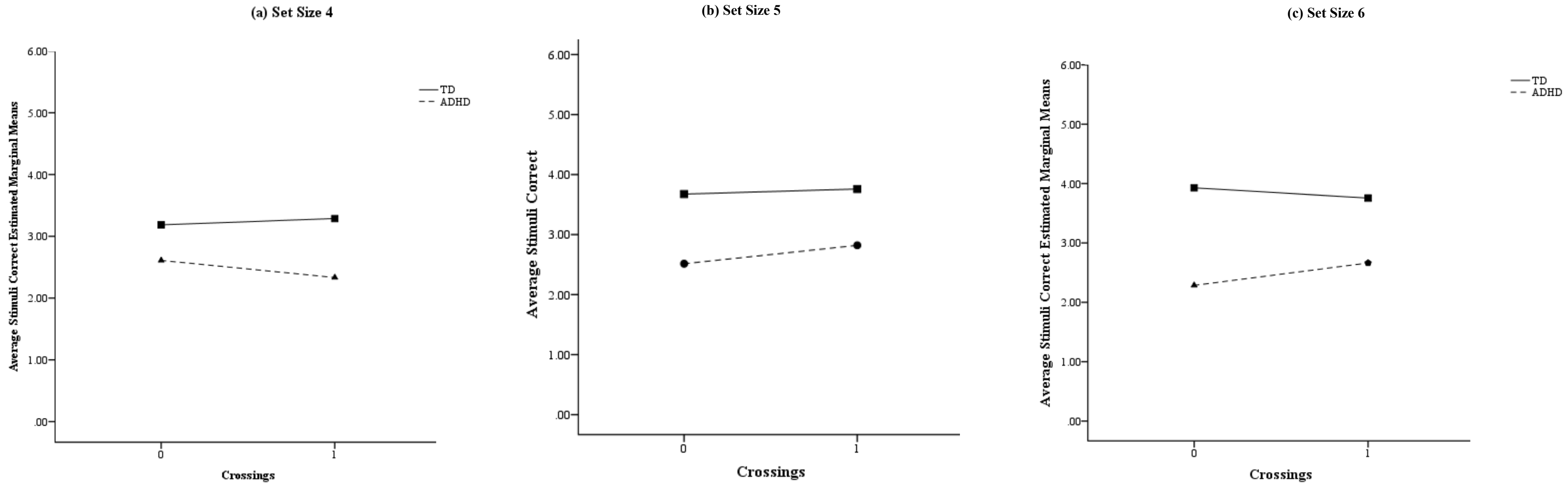
VS-WM Performance Across Set Sizes (Tier 1)



Note. TD = typically developing; ADHD = attention-deficit/hyperactivity disorder

Figure 7

VS-WM Performance Across Path Crossings Condition (Tier 3)



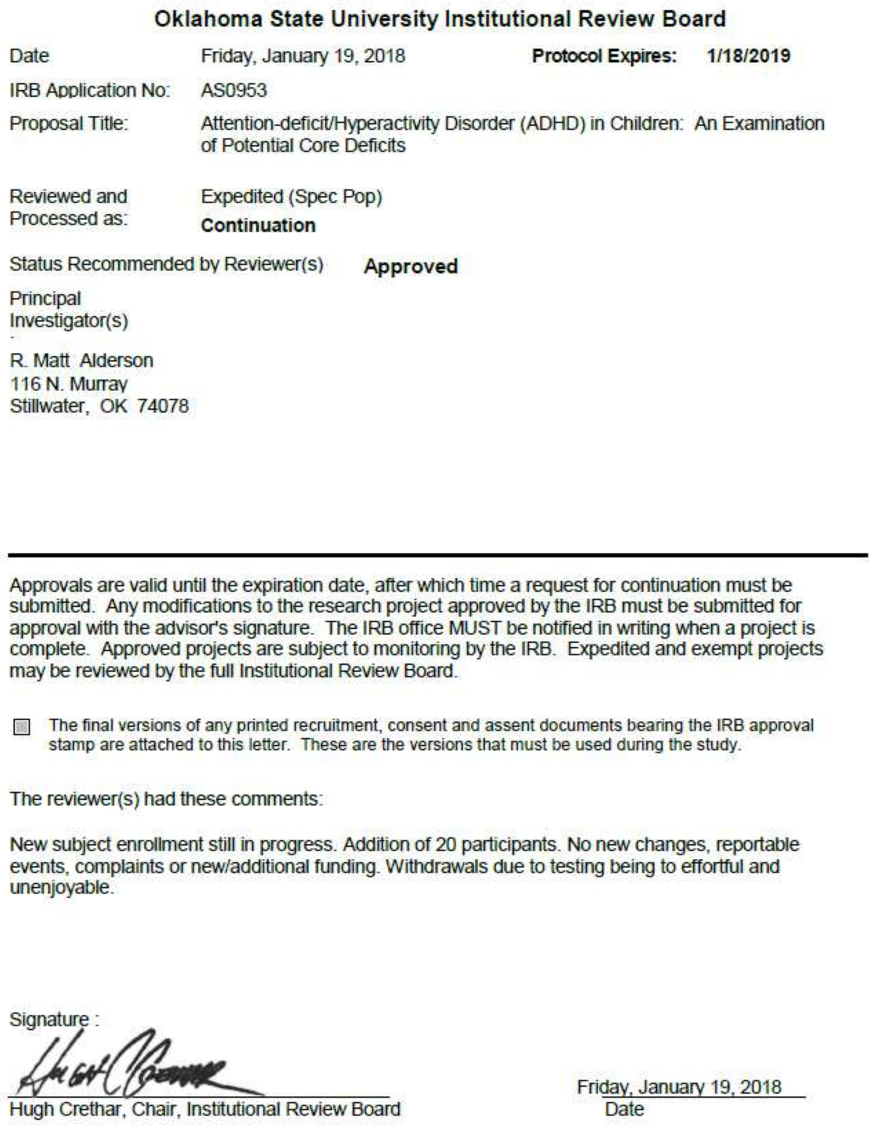
(a) Set Size 4

(b) Set Size 5

(c) Set Size 6

Note. TD = typically developing; ADHD = attention-deficit/hyperactivity disorder.

APPENDICES



Oklahoma State University Institutional Review Board

Date	Friday, January 19, 2018	**Protocol Expires:**	**1/18/2019**
IRB Application No:	AS0953		
Proposal Title:	Attention-deficit/Hyperactivity Disorder (ADHD) in Children: An Examination of Potential Core Deficits		
Reviewed and Processed as:	Expedited (Spec Pop) **Continuation**		

Status Recommended by Reviewer(s) **Approved**

Principal Investigator(s)

R. Matt Alderson
116 N. Murray
Stillwater, OK 74078

Approvals are valid until the expiration date, after which time a request for continuation must be submitted. Any modifications to the research project approved by the IRB must be submitted for approval with the advisor's signature. The IRB office MUST be notified in writing when a project is complete. Approved projects are subject to monitoring by the IRB. Expedited and exempt projects may be reviewed by the full Institutional Review Board.

☐ The final versions of any printed recruitment, consent and assent documents bearing the IRB approval stamp are attached to this letter. These are the versions that must be used during the study.

The reviewer(s) had these comments:

New subject enrollment still in progress. Addition of 20 participants. No new changes, reportable events, complaints or new/additional funding. Withdrawals due to testing being to effortful and unenjoyable.

Signature :

Hugh Crethar, Chair, Institutional Review Board

Friday, January 19, 2018
Date

VITA

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