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Working Memory and Math Skills in Children With and Without ADHD

Fatou Gaye, Nicole B. Groves, Elizabeth S. M. Chan, Alissa M. Cole, Emma M. Jaisle, Elia F. Soto, and Michael J. Kofler
Department of Psychology, Florida State University

Objective: Children with attention-deficit/hyperactivity disorder (ADHD) frequently demonstrate deficits in working memory and in multiple domains of math skills, including underdeveloped problem-solving and computation skills. The Baddeley model of working memory posits a multicomponent system, including a domain-general central executive and two domain-specific subsystems—phonological short-term memory and visuospatial short-term memory. Extant literature indicates a strong link between neurocognitive deficits in working/short-term memory and math skills; however, the extent to which each component of working/short-term memory may account for this relation is unclear. ***Method:*** The present study was the first to use bifactor (S·I-1) modeling to examine relations between each working/short-term memory subcomponent (i.e., central executive, phonological short-term memory, and visuospatial short-term memory), ADHD symptoms, and math skills in a clinically evaluated sample of 186 children ages 8–13 (M_{years} = 10.40, *SD* = 1.49; 62 girls; 69% White/non-Hispanic). ***Results:*** Structural equation modeling indicated that all three working/short-term memory components exert a significant and approximately equal effect on latent math skills (β = .29–.50, all $p < .05$) and together explain 56% of the variance in children's math achievement (R^2 = .56). Exploratory analyses indicated that teacher-reported ADHD inattentive symptoms provided a small but significant contribution to predicting latent math skills (ΔR^2 = .07) and accounted for 24% of the central executive/math association. ***Conclusions:*** These findings suggest that math difficulties in children with ADHD and clinically evaluated children without ADHD are associated, in large part, with their neurocognitive vulnerabilities in working/short-term memory and, to a lesser extent, overt ADHD symptoms.

Key Points

Question: Attention-deficit/hyperactivity disorder (ADHD) is associated with working memory deficits and difficulties with math, but which component(s) of working memory contribute to this relation? ***Findings:*** All three components of working memory predicted math performance significantly and approximately equally, and explained over half of the variance in children's math achievement even when controlling for age, sex, socioeconomic status, and ADHD symptoms. ***Importance:*** Math skills appear to be approximately equally influenced by central executive working memory and both short-term memory subsystems to the same extent for children with ADHD as they are for children without ADHD, thus informing potential targets for cognitive and academic intervention. ***Next Steps:*** Experimental and/or longitudinal work is needed to evaluate the potential causal relations between working/short-term memory and math performance in children with and without ADHD.

Keywords: attention-deficit/hyperactivity disorder, working memory, short-term memory, math achievement

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Michael J. Kofler https://orcid.org/0000-0002-8604-3647
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Correspondence concerning this article should be addressed to Michael J. Kofler, Department of Psychology, Florida State University, 1107 West Call Street, Tallahassee, FL 32306-4301, United States. Email: kofler@psy.fsu.edu

Attention-deficit/hyperactivity disorder (ADHD) is a chronic neurodevelopmental disorder that affects approximately 5% of school-aged children (Polanczyk et al., 2014) and is characterized by pervasive symptoms of inattention, hyperactivity, and/or impulsivity (American Psychiatric Association [APA], 2013). Children with ADHD frequently demonstrate deficits in working memory (e.g., Kofler et al., 2018) and in multiple domains of math skills (e.g., DuPaul et al., 2013). Experimental and longitudinal evidence implicates working memory difficulties as a causal mechanism that underlies, in part, ADHD behavioral symptom expression (Karalunas et al., 2017; Kofler et al., 2010; Rapport et al., 2009) and difficulties in other academic areas such as reading (Kofler et al., 2019). However, the extent to which underdeveloped working memory may account for math difficulties in children with ADHD is less clear (Barry et al., 2002; Martinussen et al., 2005; Rogers et al., 2011), and the evidence is mixed in terms of which specific component(s) of working memory may account for this relation (e.g., Friedman et al., 2018; Rennie et al., 2014). To that end, the present study is the first to use a bifactor modeling approach to create latent estimates of each of the three primary components of working memory (central executive, visuospatial short-term memory, phonological short-term memory; defined below) and examine relations with a latent estimate of objectively assessed math skills (computation, problem solving, fluency) in a relatively large and carefully phenotyped sample of children with and without ADHD.

ADHD and Working Memory

Working memory refers to the active, top-down manipulation of information held in short-term memory (Baddeley, 2007), supported by midlateral prefrontal and interconnected networks (Nee et al., 2013; Wager & Smith, 2003). Among the diverse models of working memory (e.g., Engle et al., 1999; Gray et al., 2017; Nee et al., 2013; Wager & Smith, 2003), the influential Baddeley (2007) model has been frequently employed to study working memory deficits in ADHD (e.g., Rapport et al., 2008) and is supported by a strong evidence base in both ADHD/clinical child (e.g., Kofler, Singh, et al., 2020) and developmental/community samples (e.g., Alloway et al., 2006; Fassbender & Schweitzer, 2006; Smith et al., 1996). In this model, working memory is viewed as a multicomponent system comprised of a domain-general central executive and two domain-specific subsystems—phonological short-term memory and visuospatial short-term memory. The central executive is the "working" component of working memory and is responsible for the continuous updating, dual processing, and serial/temporal ordering of information held in the short-term memory subsystems (Fosco et al., 2020). Phonological short-term memory is responsible for the temporary storage and maintenance of language-based verbal and auditory information, whereas visuospatial short-term memory is responsible for the temporary storage and maintenance of nonverbal visual and spatial information. The central executive, phonological short-term memory, and visuospatial short-term memory subsystems are functionally independent and anatomically distinct (e.g., Alloway et al., 2006; Fassbender & Schweitzer, 2006). A third short-term storage component called the episodic buffer was added to the model more recently and is used when information from multiple modalities must be bound and stored as a unitary episode or chunk (e.g., when learning the spatial positions of the phonological letters on a computer keyboard; Baddeley et al., 2010). The episodic buffer component was not investigated in the present study; prior experimental work suggests that the episodic buffer is likely intact in pediatric ADHD (Kofler et al., 2017; cf. Alderson et al., 2022).

Working memory deficits are pervasive in ADHD, with meta-analytic reviews indicating large magnitude differences between ADHD and non-ADHD groups (Kasper et al., 2012), and recent studies consistently reporting that between 62% and 85% of children with ADHD exhibit working memory deficits when assessed using well-validated working memory tests derived from the cognitive literature (e.g., Fosco et al., 2020; Karalunas et al., 2017; Kofler et al., 2019; Kofler, Singh, et al., 2020). While central executive deficits are consistently reported and typically large in magnitude (e.g., Fosco et al., 2020; Raiker et al., 2012), deficits in visuospatial short-term memory are frequently reported but tend to be more moderate in magnitude, and many if not most recent studies report no evidence of phonological short-term memory deficits in children with ADHD based on latent/composite indices (see Kofler, Singh, et al., 2020, for review).

Working memory deficits have been associated with the inattentive (Karalunas et al., 2017), hyperactive (Rapport et al., 2009), and impulsive (Raiker et al., 2012) symptoms of ADHD. Emerging evidence suggests that these relations may be carried via the central executive component of working memory, which predicts both parent- and teacher-reported inattentive and hyperactive/impulsive symptoms (Kofler, Singh, et al., 2020). Experimental and longitudinal studies suggest that the link between working memory and ADHD behavior is functional if not causal based on evidence that (a) manipulating working memory demands produces robust changes in ADHD behavioral symptoms (Kofler et al., 2010; Rapport et al., 2009) and (b) working memory deficits persist throughout development for most children with ADHD and covary over time with ADHD symptom severity (Brocki & Bohlin, 2006; Karalunas et al., 2017; Tillman et al., 2011). ADHD-related deficits in working memory have also been implicated in underachievement across multiple academic domains including organization and planning difficulties (Kofler et al., 2018), reduced academic success in the classroom (Kofler et al., 2017), and academic underachievement in reading (Friedman et al., 2017) and writing (Soto et al., 2021)—providing a compelling case for examining links between working memory and math for these children as described below (Re et al., 2016; Rennie et al., 2014).

ADHD and Mathematics Skills

ADHD is associated with marked impairments in math (Biederman et al., 1996; LeFever et al., 2002; Loe & Feldman, 2007). An estimated 5%–30% of children with ADHD meet criteria for math learning disorders (DuPaul et al., 2013). Further, difficulties in math are present even in children with ADHD who do not meet formal criteria for a learning disorder in mathematics (Czamara et al., 2013; Mayes et al., 2000), and these difficulties have been documented across all three ADHD symptom presentation specifiers (inattentive, hyperactive/impulsive, combined; Capano et al., 2008). In terms of specific math skills, children with ADHD demonstrate reduced math problem-solving skills (Re et al., 2016), lower conceptual math understanding (Zentall et al., 1994), and difficulties with math fluency—one's skill at quickly and efficiently solving

simple arithmetic problems within a time limit—when compared to typically developing peers (Capodieci & Martinussen, 2017).

Understanding the mechanisms and processes that underlie these math difficulties is critical given their association with adverse outcomes both concurrently and longitudinally. For example, children with ADHD who exhibit early academic difficulties in subjects such as math are at risk for later academic underachievement (Daley & Birchwood, 2010), greater absenteeism and high school dropout (Barbaresi et al., 2007), and decreased likelihood of completing a bachelor's degree (Mannuzza et al., 1993). Myriad factors have been linked to math deficits in ADHD, including inattentive symptom severity (e.g., Barry et al., 2002; Rogers et al., 2011) and underlying neurocognitive deficits (e.g., Friedman et al., 2018; Martinussen et al., 2005). With regard to ADHD symptoms, converging evidence suggests that math difficulties may be more strongly associated with inattentive relative to hyperactive/impulsive symptoms (Daley & Birchwood, 2010; Marshall et al., 1997; Tosto et al., 2015; cf. Capano et al., 2008). In terms of neurocognitive explanations, executive functioning in general (Barry et al., 2002) and working memory in particular (Antonini et al., 2016; Friedman et al., 2018) have emerged as particularly important for understanding the math-related difficulties exhibited by children with ADHD as detailed below.

Working Memory and Mathematics

Extant literature suggests that working memory is a significant contributor to math skill performance in areas such as counting, magnitude understanding, simple arithmetic, word problems, and procedural knowledge (Cragg & Gilmore, 2014; De Smedt et al., 2009; Espy et al., 2004; Xenidou-Dervou et al., 2013). Substantial overlap in cortical activation during working memory and math tasks suggests a functional relation between these processes in neurotypical children (Metcalfe et al., 2013; see Menon, 2016, for review) and provides a compelling basis for unpacking the specific components of working memory that drive this association (Raghubar et al., 2010). Within Baddeley's (2007) multicomponent framework, the central executive and two domain-specific short-term memory subsidiary systems are hypothesized to play differing roles in mathematical calculation and applied problem-solving skills (Swanson & Fung, 2016). While the phonological and visuospatial subsystems are responsible for temporarily storing verbal and visual information related to math problems, the central executive serves as a general processor that updates information in short-term memory (Re et al., 2016), retrieves task-relevant information from long-term memory (Barrouillet & Lépine, 2005), and aids in shifting between mathematical operations (Andersson, 2008). In support of this conceptualization, Simmons et al. (2012) found that central executive functioning explained unique variance in addition to accuracy, while visuospatial short-term memory predicted unique variance in symbolic magnitude comparisons and number writing. Similarly, both concurrent and 5-year longitudinal evidence indicates that visuospatial short-term memory and central executive working memory are strong predictors of math performance, while phonological short-term memory is a lesser contributor to non-word-based math problems (Bull et al., 2008; David, 2012; Geary, 2011).

ADHD, Working Memory, and Math Skills

Relatively few studies have concurrently examined working memory and math skills in children with ADHD, with the available evidence suggesting working memory–math skill associations similar to those reported from community/developmental samples (Rennie et al., 2014; Rogers et al., 2011). Of the few studies that fractionated the working memory system, one study reported that visuospatial short-term memory was the strongest predictor of a composite math measure, whereas the central executive was a lesser predictor and phonological short-term memory did not significantly predict math skills (Metcalfe et al., 2013). However, several of the tasks used in that study have been criticized for poor construct validity because they were developed to assess gross neuropsychological functioning rather than subcomponents of working memory specifically (see Snyder et al., 2015; Wells et al., 2018, for reviews). More recently, Friedman et al. (2018) addressed this limitation via an elegant study design that included tasks with strong psychometric and construct validity support for assessing each component of working memory (e.g., Kofler, Singh, et al., 2020; Wells et al., 2018), and composite estimation of each working memory subcomponent. They found that all three working/short-term memory components predicted math computation and applied problem solving, but the extent to which each component uniquely predicted math skills remains unclear from that study. Despite these methodological refinements, questions regarding working memory and math skills in ADHD remain because Friedman et al. (2018) were limited to a relatively small sample of boys, derived estimates using a regression-based approach that has been criticized recently for potentially underestimating or misestimating the phonological and visuospatial short-term memory subsystems (Gibson et al., 2018), and were unable to examine relations with math fluency or concurrently assess each working memory subcomponent's unique association with math skills.

The Present Study

Taken together, the evidence base at this time indicates well-documented associations between ADHD and working memory difficulties (Karalunas et al., 2017; Kofler, Singh, et al., 2020), ADHD and math difficulties (Czamara et al., 2013; DuPaul et al., 2013), and working memory and math skills (Swanson & Fung, 2016; Xenidou-Dervou et al., 2013). However, few clinical child studies have examined the impact of all three working memory subcomponents on math skills using well-validated tests. The present study addressed these limitations via the use of a battery of well-validated working memory tasks and standardized tests of math computation, problem-solving, and fluency skills; recruitment of a relatively large and carefully phenotyped sample of boys and girls with and without ADHD; and a bifactor (S·I-1) modeling approach that provided latent estimates of each working memory subcomponent (Eid et al., 2017, 2018). We hypothesized that (a) the central executive would be a stronger predictor of latent math achievement than either visuospatial short-term memory or phonological short-term memory; and (b) ADHD inattentive symptoms would predict math performance, both uniquely and in part via shared associations with one or more short-term/working memory components.

Method

Transparency and Openness Statement

We report how we determined our sample size, all data exclusions, all manipulations, and all measures in the study. Analyses were conducted using structural equation modeling via the R package lavaan (Rosseel, 2012) as implemented in JASP [Version 0.16.1]

(JASP Team, 2021) with full information maximum likelihood estimation of missing data. The software Omega v2 (Watkins, 2017) was used to assess the multidimensionality, construct reliability, and replicability, and explained common variance (ECV) of the working memory bifactor model. The study's design and analyses were not publicly preregistered.

Participants

The sample comprised 186 children aged 8–13 years ($M = 10.40$, $SD = 1.49$; 62 girls) from the Southeastern United States recruited through community resources to a university-based Children's Learning Clinic (CLC) between 2014 and early 2020. 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 agreed to have them participate in developmental/clinical research studies. Florida State University institutional review board approval was obtained/maintained, and all parents and children provided informed consent/assent. Sample ethnicity was mixed with 130 White/non-Hispanic (69.9%), 24 Black (12.9%), 18 multiracial (9.7%), 13 Hispanic (7.0%) children, and one Asian child (0.5%; Table 1). All children/families presented with functional English language proficiency and provided informed consent/asset in English. All study procedures were conducted in English.

Group Assignment

All children and caregivers completed a detailed, semistructured clinical interview using the Kiddie Schedule for Affective Disorders and Schizophrenia for School-Aged Children (K-SADS; Kaufman et al., 1997). The K-SADS (2013 Update) allows differential diagnosis according to symptom onset, course, duration, quantity, severity, and impairment in children and adolescents based on

Table 1
Sample and Demographic Variables

	ADHD (N = 120)		Non-ADHD (N = 66)					
Variable	M	SD	M	SD	Cohen's d	p	Possible range	Obtained range
Sex (males/females)	84/36		40/26		—	.19, *ns*	—	—
Ethnicity (A/B/W/H/M)	0/18/88/6/8		1/6/42/7/10		—	.07, *ns*	—	—
Age	10.23	1.48	10.69	1.48	0.31	.04	8.00–13.92	8.22–13.37
SES	47.87	11.11	49.46	11.51	0.14	.36, *ns*	8–66	20–66
Maternal education level (P/HS/A/B/G)	2/10/23/50/35		0/3/8/27/28		—	.28, *ns*	—	—
SFIQ	102.23	15.47	106.44	11.51	0.30	.05, *ns*	43–157	73–143
Comorbid diagnoses (no/yes)	46/74 (35 ANX, 8 ASD, 4 DEP, 14 ODD)		25/41 (19 ANX, 13 ASD, 7 DEP, 0 ODD)		—	.95, *ns*	—	—
ADHD symptoms								
ADHD-RS-4/5 attention problems (raw scores)								
Parent	19.67	5.33	15.02	7.93	−0.73	<.001	0–27	0–27
Teacher	17.00	6.26	11.26	7.86	−0.84	<.001	0–27	0–27
ADHD-RS-4/5 hyperactivity/impulsivity (raw scores)								
Parent	14.94	7.26	9.30	6.52	−0.80	<.001	0–27	0–27
Teacher	12.02	8.61	6.26	7.08	−0.71	<.001	0–27	0–27
Working memory task performance								
Phonological set size 3	2.65	0.43	2.84	0.25	0.49	.002	0.00–3.00	1.24–3.00
Phonological set size 4	3.28	0.67	3.63	0.35	0.62	<.001	0.00–4.00	1.33–4.00
Phonological set size 5	3.72	0.89	4.30	0.62	0.72	<.001	0.00–5.00	0.99–5.00
Phonological set size 6	3.27	1.20	3.98	1.22	0.59	<.001	0.00–6.00	0.33–6.00
Visuospatial set size 3	1.96	0.66	2.44	0.45	0.81	<.001	0.00–3.00	0.17–3.00
Visuospatial set size 4	2.33	0.92	3.30	0.63	1.17	<.001	0.00–4.00	0.17–4.00
Visuospatial set size 5	2.46	1.08	3.38	0.88	0.91	<.001	0.00–5.00	0.33–5.00
Visuospatial set size 6	2.23	1.08	3.31	1.128	0.99	<.001	0.00–6.00	0.33–5.67
Math skills								
Math concepts and applications	96.51	15.90	105.83	13.65	0.62	<.001	40–160	65–136
Math computation	94.82	14.32	102.65	13.76	0.56	<.001	40–160	63–142
Math fluency	91.53	11.79	100.70	12.53	0.76	<.001	40–160	63–127

Note. Working memory task performance is measured as stimuli correct per trial. Math skills reflect standard scores (age norms) on the Kaufman Test of Educational Achievement–Third Edition (KTEA-3). ADHD = attention-deficit/hyperactivity disorder; ethnicity (A = Asian, B = Black/African American, H = Hispanic/Latino, M = multiracial, W = White/non-Hispanic); Maternal education level (A = at least 1 year of college/associates degree or specialized training, B = bachelor's/4-year college degree, G = graduate school degree, HS = high school diploma or equivalent, P = partial high school); SFIQ = Short Form Intelligence Scale; SES = Hollingshead socioeconomic status; ADHD-RS-4/5 = ADHD Rating Scale. Comorbidity counts do not sum to total comorbid cases due to cases with multiple comorbidities (ANX = anxiety, ASD = autism spectrum disorder, DEP = depressive disorders, ODD = oppositional-defiant disorder). *ns* = nonsignificant.

Diagnostic and Statistical Manual of Mental Disorder, fifth edition criteria (APA, 2013) and was supplemented with age- and sex-normed parent and teacher ratings from the Behavior Assessment System for Children (BASC-2/3; Reynolds & Kamphaus, 2004) and ADHD Rating Scale (ADHD-RS-4/5; DuPaul et al., 2016). A psychoeducational report was provided to parents; participating children selected a small toy (<$5) from a prize box.

One hundred and twenty children (36 girls) met all of the following criteria and were diagnosed with ADHD based on the comprehensive psychoeducational evaluation: (a) *Diagnostic and Statistical Manual of Mental Disorder, fifth edition* diagnosis of ADHD combined (78), inattentive (36), or hyperactive/impulsive (6) presentations by the CLC's directing clinical psychologist and multidisciplinary team based on K-SADS and differential diagnosis considering all available clinical information indicating onset, course, duration, and severity of ADHD symptoms consistent with the ADHD neurodevelopmental syndrome; (b) borderline/clinical elevations on at least one parent *and* one teacher ADHD subscale (i.e., >90th percentile); and (c) current impairment based on parent report. Children with any current ADHD presentation specifiers were eligible given the instability of ADHD presentations (Lahey et al., 2005; Valo & Tannock, 2010; Willcutt et al., 2012).

Our standard assessment battery also included norm-referenced child internalizing disorder screeners, and additional standardized measures were administered clinically as needed to inform differential diagnosis and accurate assessment of comorbidities (e.g., child clinical interviews, additional testing). Several children with ADHD also met the criteria for common comorbidities based on this comprehensive psychoeducational evaluation, including anxiety disorders (58%), oppositional-defiant disorder (21%), autism spectrum disorders (ASDs; 14%), and depressive disorders (7%). To improve generalizability, given that comorbidity is the norm rather than the exception for children with ADHD (Wilens et al., 2002), these children were retained in the sample. In addition, 20 children with ADHD screened positive for specific learning disorders in math ($n = 12$) and/or reading ($n = 8$). Positive screens for learning disorders were defined based on scores ≥1.5 *SD* below age norms on one or more Kaufman Test of Educational Achievement–Third Edition (KTEA-3) academic skills battery reading and math subtests, as specified in *Diagnostic and Statistical Manual of Mental Disorder, fifth edition* (APA, 2013). Given the epidemiological evidence for high comorbidity between ADHD and math disability (Capano et al., 2008; DuPaul et al., 2013; Zentall, 2007), and because positive screens in the present study were defined based on scores on our primary outcome variables, these children were retained to provide a broader range of math scores. Thirty-four (28.3%) of the 120 children with ADHD were prescribed psychostimulant medication. Children prescribed psychostimulant medication received their usual dose on the psychoeducational testing day (i.e., when the math achievement tests were administered). However, medication was withheld for ≥24 hr prior to research testing sessions (i.e., when the working memory tasks were administered). Sensitivity analyses indicated that the pattern of results below was unchanged when ADHD medication status was added as a covariate.

Additionally, 66 children (26 girls) completed the same comprehensive psychoeducational assessment and did not meet the criteria for ADHD. To control for comorbid diagnoses in the ADHD group, participants in this group included both neurotypical children (38.5%) and children with anxiety disorders (49%), ASDs (37%), and depressive disorders (14%). Neurotypical children had normal developmental histories and nonclinical parent/teacher ratings, were recruited through community resources, and completed the same evaluation as clinically referred children. Four non-ADHD children screened positive for specific learning disorders in math ($n = 2$) and/or reading ($n = 2$) based on the criteria described above. None of the children presented with gross neurological, sensory, or motor impairments that would preclude valid test administration, history of seizure disorder, intellectual disability, psychosis, or nonstimulant medication that could not be withheld for testing.

Procedure

Working memory testing occurred as part of a larger battery that involved one to two sessions of approximately 3 hr each. All tasks were counterbalanced across sessions to minimize order effects. Children received brief breaks after each task and preset longer breaks every two to three tasks to minimize fatigue. Performance was monitored by an examiner at all times, who was seated just outside of the testing room (out of the child's view) to provide a structured setting while minimizing performance improvements associated with demand characteristics. Math skills were evaluated during a separate 3-hr psychoeducational testing session administered according to standard clinical practice protocols. Due to the COVID-19 pandemic, testing procedures were modified for the final eight participants according to COVID-19 safety protocols (e.g., face masks, increased physical distancing during testing, increased cleaning/sanitation procedures). Sensitivity analyses indicated that the pattern and interpretation of results reported below were unchanged with these eight cases excluded.

Measures

Working Memory

The Rapport computerized working memory tasks were developed to assess working memory based on the Baddeley (2007) model (Rapport et al., 2008). These tasks correctly classify children with versus without ADHD at similar rates as parent and teacher ADHD rating scales (Tarle et al., 2017) and predict ADHD-related impairments in objectively measured activity level (Rapport et al., 2009), attentive behavior (Kofler et al., 2010), impulsivity (Raiker et al., 2012), delay aversion (Patros et al., 2015), inhibitory control (Alderson et al., 2010), reading comprehension (Friedman et al., 2017), and academic, peer, and family dysfunction (Kofler et al., 2011, 2017). Evidence for reliability and validity includes high internal consistency ($\alpha = .82-.97$; Kofler et al., 2018), 1–3 week test–retest reliability (.76–.90; Sarver et al., 2015), and expected magnitude relations with criterion working memory complex span ($r = .69$) and updating tasks ($r = .61$; Wells et al., 2018). Six trials per set size were administered in randomized/unpredictable order (3–6 stimuli/trial; 1 stimuli/second) as recommended (Kofler et al., 2017). Five practice trials were administered before each task (80% correct required). Higher scores indicate better performance at each set size for both tasks.

Phonological Working Memory Task. Children were presented with a series of jumbled numbers and one letter that was never presented first or last to minimize primacy/recency effects. The letter was counterbalanced to appear equally in each of the other positions. Children were instructed to recall the numbers from least to greatest and the letter last (e.g., 4H62 recalled as 246H).

Visuospatial Working Memory Task. Children were shown nine squares arranged in three offset vertical columns on a computer monitor. A series of 2.5 cm dots (3, 4, 5, or 6) were presented sequentially (1 stimuli/second). No two dots appeared in the same square on a given trial. All dots were black except one red dot that was never presented first or last to minimize primacy/recency effects. Using a modified keyboard, children were instructed to recall the serial position of the black dots and put the red dot last.

Bifactor (S·I-1) Model of Working Memory. Bifactor (S·I-1) modeling was selected a priori given our goal of identifying process-pure, latent estimates of domain-general central executive working memory and the domain-specific phonological and visuospatial short-term memory subsystems. This decision was informed by the Baddeley (2007) multicomponent framework, which specifies a single central executive system that operates on the structurally and functionally independent phonological and visuospatial short-term storage buffers. In this model, shared variance across working memory tests with different stimulus modalities (i.e., visuospatial vs. phonological) is attributed to domain-general working memory (i.e., the “central executive”), whereas variance unique to each task is attributable to the phonological and visuospatial short-term memory processes, respectively (see Rapport et al., 2008, for review). Support for this model includes replicated evidence that the phonological and visuospatial storage systems are functionally and anatomically distinct, as well as replicated evidence supporting a single, domain-general central executive rather than separate central executive components for processing phonological and visuospatial information (Alloway et al., 2006; Baddeley, 2007; Smith et al., 1996).

As recommended by Eid et al. (2018) and following Kofler, Singh, et al. (2020), the present study used a bifactor (S·I-1) structure, such that all 8 indicators (phonological and visuospatial set sizes 3, 4, 5, and 6) loaded onto the general factor (i.e., central executive) and a subset of indicators also loaded onto each specific short-term memory factor (i.e., visuospatial or phonological). As described by Eid et al. (2018), to properly fit the bifactor model, one or more items must load onto the general factor but not onto any specific factor. These items are called “reference facets” and define the meaning of the general factor (in this case, “central executive”). To ensure that the general factor reflected domain-general central executive working memory, we selected two reference facets: one phonological and one visuospatial (Heinrich et al., 2020). We chose set size 3 from each task given Baddeley’s (2007) conceptualization that central executive demands remain relatively constant despite increasing set size; increasing set size is viewed as primarily a manipulation of short-term memory demands.[1] To allow for maximal discrimination between constructs in our bifactor (S·I-1) model, the general factor is modeled as uncorrelated with each specific factor (Eid et al., 2018), and the specific factors are also modeled as uncorrelated with each other. This representation is based on the underlying assumption that an individual’s score on an item reflects at least two distinct sources of variance (i.e., the general factor and the specific factor).

Mathematical Skills

Kaufman Test of Educational Achievement (KTEA-3)

The KTEA-3 (Kaufman & Kaufman, 2014) was used to assess children’s mathematical skills (α = .95−.98; 1–2-week test–retest = .87−.95). As described below, a latent math variable was created using the three mathematical subtests of the KTEA-3: Math Concepts & Applications, Math Computation, and Math Fluency. *Math Concepts & Applications* encompasses children’s skill at applying mathematical calculation principles to real-life situations. Application skills are measured in areas such as number concepts, operation concepts, time, money, measurement, geometry, fractions, decimals, data investigation, and higher math concepts. *Math Computation* refers to children’s skill at completing math calculations and is assessed across multiple skill domains including counting, number identification, arithmetic operations, fractions, decimals, square roots, exponents, and algebra. *Math Fluency* refers to children’s skill at quickly solving simple arithmetic problems and is measured by the accuracy of addition, subtraction, multiplication, and division problems completed within 1 min. Standard scores (age norms) for each mathematical skill were obtained by comparison to the nationally representative standardization sample (N = 2,050). Higher scores indicate greater achievement.

ADHD Symptoms

ADHD symptom frequency and severity were assessed using the ADHD Rating Scale for *DSM-IV/5* (ADHD-RS-4/5; DuPaul et al., 2016). The ADHD-RS-4/5 includes 18 items across two symptom subscales: inattention (nine items) and hyperactivity/impulsivity (nine items). Psychometric support for this measure includes high internal consistency (α = 0.94) and test–retest reliability (r = 0.79–0.85; DuPaul et al., 2016). Higher scores indicate higher quantity and severity of ADHD symptoms.

Intellectual Functioning and Socioeconomic Status

Intellectual functioning (IQ) was estimated using the 4-subtest Wechsler Intelligence Scale for Children–Fifth Edition Short-Form IQ (Vocabulary, Similarities, Matrix Reasoning, Figure Weights), which has a validity coefficient of $r = .90$ and correlates $r_{ss} = .96$ with the full, 7-subtest Wechsler Intelligence Scale for Children–Fifth Edition Full-Scale Intelligence Quotient (Sattler et al., 2016). Socioeconomic status (SES) was estimated using the Hollingshead scoring based on caregiver(s)’ occupation and education (Cirino et al., 2002).

Data Analysis Overview

Our primary analyses are organized into three analytic tiers. Age, sex, and SES were included as covariates in all tiers/models. In the first tier, we built the working memory measurement model that included a general central executive factor (all eight task performance indicators loading onto a single factor), as well as phonological and visuospatial short-term memory-specific factors. This measurement model was compared to a one-factor working memory model (all eight task performance variables loading onto a single factor with no short-term memory-specific factors) to evaluate model fit. A latent math variable based on the three KTEA-3 subtests (Math Concepts & Applications, Math Computation, and Math Fluency) was also created/tested in Tier 1.

[1] Please see Kofler, Singh, et al. (2020) for evidence from a subset of the current sample that model fit and associations with ADHD symptoms were unchanged when different set sizes were selected as reference facets, as well as evidence that (a) the phonological and visuospatial short-term memory specific factors were not significantly correlated in exploratory analyses and (b) allowing them to correlate did not significantly improve model fit.

In Tier 2, we created the primary structural model to test the extent to which each short-term/working memory component predicted math performance. Finally, in Tier 3, we added continuous estimates of children's attention problems and hyperactivity/impulsivity as intermediate (i.e., conditional) effects between each short-term/working memory component and each math outcome. Conditional effects modeling was used in Tier 3 because it allowed shared variance among predictors to be parsed according to theory and previous research. Pathway directionality was specified a priori based on the available literature reviewed above. Notably, the cross-sectional design precludes testing competing models regarding directional effects of working memory and math skills or math skills and ADHD symptoms (i.e., reversing arrows does not distinguish plausible models; Thoemmes, 2015). Inattention and hyperactivity/impulsivity were included separately based on evidence that they differentially predict relations between working memory and other ADHD-related impairments (e.g., Bunford et al., 2015; Kofler et al., 2018). Bias-corrected bootstrapping with 5,000 resamples was used as recommended (e.g., Preacher et al., 2007). For all pathways, effects are considered statistically significant if their 95% confidence intervals (CIs) do not contain zero. Effect ratios (ER) for significant indirect effects indicate the proportion of the total effect (c pathway) that is conveyed via the indirect pathway (ab; i.e., ER = ab/c).

For all confirmatory models, absolute and relative fit were tested. Adequate model fit is indicated by comparative fit index and Tucker–Lewis index (TLI) $\geq .90$, and root-mean-square error of approximation (RMSEA) $\leq .10$. The χ^2 difference test was used to evaluate nested model fit; lower chi-square values indicate the preferred model (Satorra & Bentler, 2010). For the working memory bifactor (S·I-1) measurement model, omega total (ω), omega subscale (ωs), ECV, and the percentage of uncontaminated correlations (PUC) were also computed. Omega total (ω) and omega subscale (ωs) index the reliability of the general factor (working memory) and specific factors (phonological and visuospatial short-term memory) by providing estimates of the proportion of variance attributable to sources of common and specific variance, respectively; values $> .70$ are preferred (Rodriguez et al., 2016a). ECV indicates the proportion of reliable variance explained by each factor. The PUC is used to assess potential bias from forcing unidimensional data into a multidimensional (bifactor) model. When general factor ECV $> .70$ and PUC $> .70$, bias is considered low and the instrument can be interpreted as primarily unidimensional (i.e., the increased complexity of the bifactor structure is likely not warranted; Rodriguez et al., 2016b). Construct replicability (H) values $> .80$ suggest a well-defined latent variable that is more likely to be stable across studies (Watkins, 2017).

All items showed the expected range of scores and were screened for normality (all skewness $< |2|$; all kurtosis $< |3|$). δ scaling with maximum likelihood estimation with robust standard errors was used to handle any nonnormality (Kline, 2016). Standardized residuals were inspected for magnitude (all positive and ≤ 1, indicating no evidence of localized ill fit). Directionality of parameter estimates was inspected.

Power Analysis

A series of Monte Carlo simulations were run using Mplus7 (Muthén & Muthén, 2012) to estimate the power of our proposed bifactor models for detecting significant factor loadings of the expected magnitude, given a sample size of 186, power $(1 - \beta) \geq .80$, $\alpha = .05$, and 10,000 simulations per model run. This process compiled the percentage of model runs that resulted in statistically significant estimates of model parameters. Standardized factor loadings and expected residual variances for observed variables were imputed iteratively to delineate the proposed bifactor model. For the Tier 1 analyses, results indicated that our measurement model is powered to detect standardized factor loadings $\geq .52$, which falls well below the loadings for these tasks in previous factor analytic studies (e.g., Kofler et al., 2018). For the Tier 2 analyses, our structural model is powered to detect associations of $r \geq .35$ between each short-term/working memory component and each math outcome. Finally, based on the Rweb quantpsy utility, for $\alpha = .05$ and 29 degrees of freedom for our most complex Tier 3 model, our $N = 186$ is powered to differentiate between an adequate (RMSEA = .05) and poor fitting model (RMSEA = .10) at power $(1 - \beta) = .92$. Thus, the study is sufficiently powered to address our primary aims (Preacher & Coffman, 2006).

Results

Preliminary Analysis and Group Differences

All independent and dependent variables were screened for univariate outliers, defined by values above or below 3 *SD* of the within-group mean. This process identified 0.28% (ADHD group) and 0.30% (non-ADHD group) of data points, which were corrected to the most extreme value of 3 *SD* above or below the within-group mean. Missing data rates were low (0.14%) and were addressed using full information maximum likelihood estimation. Task data from subsets of the current battery have been reported for subsets of the current sample to examine conceptually unrelated hypotheses (please see Groves et al., 2022). Performance data on the study's primary outcome (KTEA math scores) have not been reported for any children in the current sample.

All parent- and teacher-rated ADHD scales were higher for children with ADHD relative to children without ADHD as expected (Table 1). In addition, children with ADHD demonstrated impairments on all eight phonological and visuospatial working memory performance variables ($d = 0.49$–1.17; all $p < .01$) and all three math tests ($d = 0.56$–0.76; all $p < .001$) relative to children without ADHD. There was no significant evidence to indicate differences in SES ($p = .36$) or IQ ($p = .05$), whereas children with ADHD were slightly younger than children without ADHD ($M_{\text{age}} = 10.23$ vs. 10.69, $p = .04$). As noted above, age, sex, and SES were controlled in all analyses. IQ was not included as a covariate based on compelling statistical, methodological, and conceptual rationale against covarying IQ when investigating cognitive processes in ADHD (Dennis et al., 2009), and because IQ appears to reflect, in part, an outcome rather than a cause of working memory abilities (e.g., Engle et al., 1999). In other words, covarying IQ would preclude conclusions regarding working memory by fundamentally changing our primary predictor variables and removing significant variance associated with our predictors and outcomes of interest (Dennis et al., 2009).

Tier 1: Measurement Models

Working/Short-Term Memory Abilities

First, we created a one-factor working memory measurement model in which all eight indicators loaded significantly onto the domain-general working memory factor ($\beta = .49$–$.77$, all $p < .001$).

Table 2
Model Fit Statistics

Model	CFI	TLI	RMSEA (90% CI)	SRMR	$\chi^2(df)$	$\Delta\chi^2(df)$	ω	ω*s*	ECV	PUC	H
Tier 1: Measurement models											
Working memory single factor	0.84	0.79	0.12 [.10, .14]	0.07	143.67 (41) $p < .001$	—	—	—	—	—	—
Short-term/working memory bifactor (S·I-1)	0.95	0.90	0.08 [.05, .11]	0.05	64.38 (29) $p < .001$	79.29 (12) $p < .001$	.88	.77 (PH) .83 (VS)	.68 (CE) .16 (PH) .16 (VS)	.57	.83 (CE) .48 (PH) .48 (VS)
Math latent variable	1.00	1.00	0.02 [0, .12]	0.02	4.37 (4) $p = .36$	—	—	—	—	—	—
Tier 2: Math prediction model	0.96	0.93	0.06 [.04, .08]	0.05	98.35 (56) $p < .001$	—	—	—	—	—	—
Tier 3: Intermediate effects											
Inattentive symptoms	0.96	0.94	0.06 [.04, .08]	0.04	102.33 (63) $p = .001$	—	—	—	—	—	—
Hyperactive-impulsive symptoms	0.95	0.92	0.06 [.04, .08]	0.04	111.21 (63) $p < .001$	—	—	—	—	—	—

Note. CFI = comparative fit index; TLI = Tucker–Lewis index; CI = confidence interval; RMSEA = root-mean-square error of approximation; SRMR = standardized root-mean-square residual; ω = omega total (general working memory factor); ω*s* = omega subscale (specific short-term memory factors); ECV = explained common variance; PUC = percent of uncontaminated correlations; H = construct replicability. Omega (ω) and all columns to its right are only computed for bifactor models; PH = phonological short-term memory; CE = central executive working memory; VS = visuospatial short-term memory.

However, this model did not show adequate fit (Table 2). Next, we built the working/short-term memory bifactor (S·I-1) model by adding the visuospatial and phonological short-term memory-specific factors to the one-factor measurement model. As shown in Table 2, this model included the domain-general central executive (general factor) and the domain-specific phonological short-term memory and visuospatial short-term memory factors (specific factors). This model showed excellent fit, all indicators loaded significantly onto their hypothesized factors (all $p < .001$), and model fit was significantly improved relative to the one-factor working memory measurement model, $\Delta\chi^2(12) = 79.29$, $p < .001$. The proportion of uncontaminated correlations and ECV were both <.70, supporting the multidimensionality of the data (PUC = .57, ECV = .68; Rodriguez et al., 2016b; Watkins, 2017). Reliability was high for the general factor (ω = .88) and both specific factors (ω*s* = .77–.83). Thus, the working/short-term memory bifactor (S·I-1) model was retained for Tiers 2 and 3.

Math Skills

In Tier 1, we also used scores from the K-TEA-3 math subtests (math concepts and applications, math computation, and math fluency) to create the latent math performance factor. All three subtests loaded significantly onto the latent math factor (β = .65–.95, all $p < .001$), and the model demonstrated adequate fit (Table 2).

Tier 2: Primary Analyses—Working Memory and Short-Term Memory as Predictors of Math Achievement

Next, we created a structural model with the three short-term/working memory components predicting math skills.[2] The model showed excellent fit as shown in Table 2. Results indicated that central executive working memory (β = .50, $p < .001$), phonological short-term memory (β = .45, $p < .001$), and visuospatial short-term memory (β = .29, $p = .03$) were all significant predictors of math performance (Figure 1). Together, the model explained 56% of the variance in children's math skills ($R^2 = .56$).

Next, we tested a model in which the three regression pathways (i.e., central executive, phonological short-term memory, and visuospatial short-term memory predicting math skills) were constrained to be equal and conducted a chi-square difference test to compare this model to the primary model above (where the three pathways were allowed to be freely estimated). Interestingly, there was no significant difference in model fit between these two models, $\Delta\chi^2(2) = 1.93$, $p = .38$, suggesting that there is no significant difference in the strength of relations between each working/short-term memory component and math performance. In other words, all three working/short-term memory components contributed significantly and approximately equally to the prediction of children's math skills.

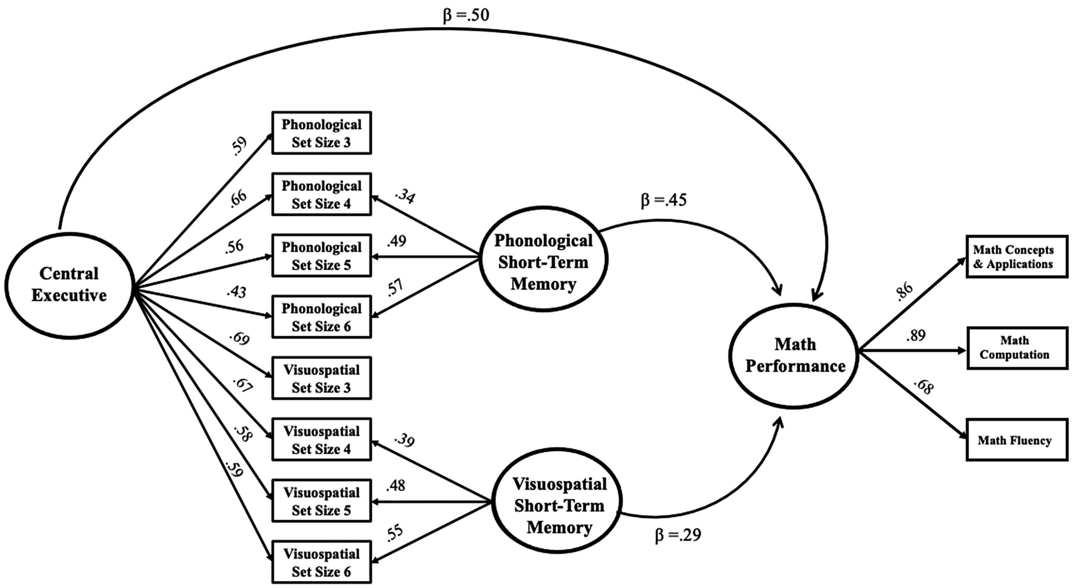
Tier 3: Exploratory Analyses—ADHD Symptoms as Intermediate Effects Between Short-Term/Working Memory and Math Achievement

Finally, we added teacher-rated inattentive and hyperactive/impulsive symptoms as intermediate effects between each of the

[2] Age, sex, and SES were controlled for in the Tiers 2 and 3 models as noted above. Older age predicted better developed central executive working memory abilities (β = .43, $p < .001$), but lower standardized math achievement (β = −.27, $p < .001$), consistent with evidence that children with ADHD tend to fall further behind their peers academically each year (Latimer et al., 2003; Schultz et al., 2009). Male sex predicted better developed visuospatial short-term memory abilities (β = −.26, $p = .02$). Finally, higher SES predicted better developed visuospatial short-term memory abilities (β = .30, $p = .01$). In contrast, age did not significantly predict phonological short-term memory ($p = .07$) or visuospatial short-term memory ($p = .08$); sex did not significantly predict math achievement ($p = .91$), central executive working memory abilities ($p = .41$), or phonological short-term memory abilities ($p = .16$); and SES did not significantly predict math achievement ($p = .19$), central executive working memory abilities ($p = .94$), or phonological short-term memory abilities ($p = .05$).

Figure 1

Bifactor (S·I-1) Model of Central Executive Working Memory (General Factor) and Short-Term Memory (Phonological and Visuospatial Specific Factors) Predicting Math Performance



Note. Latent math performance variable estimated using the three Kaufman Test of Educational Achievement–Third Edition (KTEA-3) math subtest scores (Math Computation, Math Concepts & Application, and Math Fluency). Standardized loadings are shown (all $p < .001$). Age, sex, and SES are controlled for but not depicted for clarity. SES = socioeconomic status.

three working/short-term memory components and math performance to estimate the extent to which the relations detected are conveyed via working memory's role in regulating behavior. Reporting is truncated for readability. Adding ADHD symptoms to the model resulted in a small but significant increase ($p < .001$)[3] in variance accounted (R^2 = .63 vs. .56), with inattentive ($\beta = -.29$, 95% CI excludes 0.0) but not hyperactive/impulsive symptoms (95% CI includes 0.0) uniquely predicting math difficulties. Better developed central executive working memory predicted lower inattentive ($\beta = -.40$, 95% CI excludes 0.0) and hyperactive/impulsive symptom severity ($\beta = -.24$, 95% CI excludes 0.0). In contrast, neither phonological short-term memory nor visuospatial short-term memory were associated with ADHD symptom frequency/severity (95% CIs include 0.0). Finally, there was a significant indirect effect of the central executive on math performance via the inattentive symptom pathway (ab pathway: β = .12, 95% CI excludes 0.0, ER = .24), suggesting that 24% of working memory's association with math skills is shared with inattentive symptoms. In contrast, there was no evidence of indirect effects of phonological or visuospatial short-term memory on math performance via the inattentive or hyperactive/impulsive pathways (ab pathway: 95% CIs include 0.0).

Tier 4: Sensitivity Analyses

Taken together, the primary analyses above suggest that all three working memory subcomponents contribute uniquely and approximately equally to the prediction of children's math achievement, with the central executive/math association shared in part with the central executive's role in regulating attention. To probe the robustness of these results, we conducted a series of sensitivity analyses to determine the extent to which results may have been impacted by our a priori decisions to (a) create a latent math performance variable; (b) include children with common comorbidities beyond ADHD in the sample; (c) model ADHD symptoms based on teacher report; and (d) maximize variability in predictor and outcome scores by including children with and without ADHD in the same model. First, we repeated the Tier 2 analyses with the working/short-term memory components predicting each math KTEA-3 subtest (math concepts and application, math computation, and math fluency) individually rather than predicting a latent math variable. The pattern, significance, and interpretation of results were highly consistent with the primary Tier 2 results, with the exception that visuospatial short-term memory was not a significant predictor of math computation ($p = .07$) despite predicting math concepts/applications and fluency (both $p < .05$). Second, we repeated the primary Tier 2 model two more times: once with overall comorbidity (N/Y) included as a covariate and once with separate covariates for anxiety (N/Y) and ASD (N/Y; depression and oppositional-defiant disorder [ODD] were not included due to low cell counts as shown in Table 1). Results indicated that the pattern, significance, and interpretation were unchanged in both cases, and none of the covariates significantly predicted math or any of the working memory/short-term memory components (all $p > .06$).

Next, we repeated the Tier 3 intermediate effects analyses using parent- instead of teacher-rated ADHD symptoms (parent and

[3] Because the models with versus without ADHD symptoms were not nested, we estimated whether adding ADHD symptoms to the model produced a significant increase in model R^2 by comparing the model with ADHD symptoms pathways allowed to be freely estimated with a nested model in which ADHD symptoms were included but not allowed to predict/be predicted by other variables in the model.

teacher reports correlated r = .41 for both inattentive and hyperactive/impulsive symptoms in the current sample). Once again, the pattern, significance, and interpretation of results were highly consistent with the primary results with three minor exceptions: (a) the central executive did not significantly predict parent-rated hyperactive/impulsive symptoms (95% CI includes 0.0) despite predicting inattentive symptoms (95% CI excludes 0.0); (b) parent-rated inattentive symptoms did not significantly predict children's math skills (95% CI includes 0.0); and (c) the indirect effect of central executive working memory on math performance via the inattentive symptom pathway was no longer significant (95% CI includes 0.0). Importantly, however, the primary finding that all three working/short-term memory components significantly predicted math skills was unchanged when parent ratings were substituted for teacher ratings (all 95% CIs exclude 0.0). Finally, we probed the extent to which the findings inform relations between working/short-term memory and math skills for children with ADHD specifically. This involved repeating the primary Tier 2 model one more time, this time including only children diagnosed with ADHD (n = 120). The results were highly consistent with the primary results reported above, including significant effects of central executive (β = .49, p = .01), phonological short-term memory (β = .43, p = .02), and visuospatial short-term memory (β = .32, p = .02) on math skills, with no significant difference between the constrained/unconstrained models, $\Delta\chi^2(2)$ = 2.67, p = .26, indicating that all three components significantly and similarly predicted math skills for children with ADHD (R^2 = .54).[4]

Discussion

The present study was the first to apply the bifactor (S·I-1) modeling technique to examine the relations among the three components of the working memory system (central executive, phonological short-term memory, and visuospatial short-term memory), ADHD symptoms, and math skills. Additional strengths of the study include the use of a multitrait, multimethod, and multitask design as well as the recruitment of a relatively large, clinically evaluated, and carefully phenotyped sample. Overall, the current findings indicated that all three working/short-term memory components are implicated to similar degrees, and collectively account for 56% of the variance in children's math skills. In addition, we found that the central executive/math relation was conveyed in part via their shared association with ADHD inattentive symptoms, whereas neither short-term memory subsystem was associated with ADHD symptoms.

Of primary interest in the present study was the extent to which specific components of the working/short-term memory system were associated with children's math performance. Understanding the nature of these relations is crucial given the high rates of co-occurring working memory and math deficits in children with and without ADHD (Maehler & Schuchardt, 2016) and has the potential to inform targets for intervention (Peng et al., 2016). Overall, the findings of this study were highly consistent with developmental literature linking children's working memory abilities and math achievement (Bull et al., 2008; Geary, 2011) and extended these findings by providing evidence that all three working/short-term memory components are important for understanding math skill development in children with ADHD as well as clinically evaluated children without ADHD. In addition, our findings were generally consistent with several studies linking central executive processes with math problem-solving (Geary et al., 2012) and growth in math (Jerman et al., 2012), as well as studies demonstrating unique central executive/math relations above and beyond other predictors such as reading and computational knowledge (Swanson et al., 2008). Although some researchers have posited that the central executive is more important for math problem solving (Lemaire, 1996) than phonological and visuospatial short-term memory (Swanson, 2006), the present study provides evidence that these three short-term/working memory components are approximately equally important for understanding math skills for children with ADHD and potentially for clinically evaluated children more generally. This finding is consistent with studies that have reported unique relations between all three components and math (Zheng et al., 2011) and extends this evidence base to include children with neurodevelopmental disorders such as ADHD that are associated with increased risk for math difficulties (Friedman et al., 2017).

In terms of short-term memory contributions, the findings from this study add to a mixed literature suggesting differing strengths of associations between phonological short-term memory, visuospatial short-term memory, and math performance (see Friso-Van den Bos et al., 2014, for review). For example, some studies report that visuospatial short-term memory (along with the central executive) contributes to arithmetic knowledge acquisition and math problem solving, highlighting the inherently spatial nature of numerical magnitudes (Dehaene et al., 1993; Mix & Cheng, 2012; Seron et al., 1992) and importance of mental representations of numbers in space (e.g., mental number line representations) for the successful completion of math problems (Geary, 2011; Menon, 2016; Metcalfe et al., 2013). Similarly, our findings were generally consistent with evidence linking phonological short-term memory with the encoding and maintenance of verbal codes that are used during operations such as counting and holding partial solutions during mathematical problem solving (Bull et al., 2008; Imbo & LeFevre, 2010). While some studies have failed to find support for a unique relation between phonological short-term memory and math (Fürst & Hitch, 2000; Gathercole & Pickering, 2000; Simmons et al., 2012), our findings are consistent with others who suggest that both working memory and short-term memory uniquely predict children's math performance (Swanson & Kim, 2007).

The present study found that all three short-term/working memory subcomponents contributed significantly to predicting children's math performance. This pattern was generally consistent with emerging evidence that replicated across two clinical trials suggesting that neurocognitive training protocols specifically targeting central executive working memory abilities appear to demonstrate efficacy for improving math problem-solving skills in children with ADHD (Singh et al., 2022). In contrast, at first glance, our findings appear inconsistent with meta-analytic evidence that short-term memory training protocols generally do not produce far-transfer improvements in children's math performance (Aksayli et al., 2019; Rapport et al.,

[4] In addition, we conducted a multigroup (ADHD, non-ADHD) structural equation model to further explore potential differences in model estimation between children with and without ADHD. We found that constraining the pathways between groups to be equal did not reduce model fit, $\Delta\chi^2(3)$ = 2.80, p = .42, thus providing further evidence that all three components of working/short-term memory predict math performance similarly in children with ADHD as well as clinically evaluated children without ADHD. These exploratory findings should be considered preliminary given the relatively small non-ADHD sample size (n = 66).

2013). One potential explanation for this incongruence may be that extant short-term memory training interventions have been unable to produce large enough changes in short-term memory to produce detectable changes in math skills.

For instance, short-term memory training produces medium magnitude improvements in short-term memory for children with ADHD based on meta-analysis ($d = 0.63$; Rapport et al., 2013). Given the estimated relations between visuospatial/phonological short-term memory and math found in the present study ($\beta = .29-.45$), we might expect that a $d = 0.63$ improvement in short-term memory could correspond with, at best, small improvements of $d = 0.18$–0.28 in math that would require a relatively large sample size to detect (see Rapport et al., 2013, for discussion of how maximum expected far-transfer treatment effects can be estimated by multiplying the magnitude of improvement in the treatment target by the relation between the treatment target and outcome). In contrast, central executive working memory training has been associated with large magnitude improvements in central executive abilities ($d = 0.96$–1.25 across studies; Kofler et al., 2018; Kofler, Wells, et al., 2020), with corresponding expected maximum far-transfer improvements in math based on the present study's central executive/math estimate of $d =$ 0.48–0.63 that would be detectable with more modest sample sizes. Of course, this hypothesis is speculative given that the present study did not assess intervention effects but is generally consistent with Treatment × Time interaction estimates of far-transfer improvements in math of $d = 0.56$–0.76 following central executive training relative to far-transfer math improvements of $d = 0.15$ following short-term memory training (Rapport et al., 2013; Singh et al., 2022).

Limitations

The present study has several strengths, including a relatively large and clinically evaluated sample of children, and the multimethod, multi-informant, and multitask design. However, the following limitations should be considered when interpreting results. First, there were minor discrepancies between the exploratory models based on whether we used teacher or parent perceptions of children's ADHD symptoms, which correlated moderately with each other ($r = .41$) as expected (Antrop et al., 2002; Cho et al., 2011; Papageorgiou et al., 2008). This may reflect true differences in the manifestation of ADHD behavioral symptoms across contexts (i.e., school vs. home) and the impact of these differences on academic performance (Verhulst et al., 1994). Alternatively, this may reflect differences in the precision of teacher and parent-rated ADHD symptoms, consistent with (a) prior evidence that teacher ratings may outperform parent ratings in terms of specificity, sensitivity, and overall classification of ADHD (Tripp et al., 2006); and (b) the current findings that teacher but not parent ADHD ratings were predictive of children's math skills. Next, this study had a relatively large sample of children with ADHD, which provided a wide range of working/short-term memory abilities given the well-documented heterogeneity in executive function abilities among children with ADHD (e.g., Kofler et al., 2018) that was expected to maximize our likelihood of detecting relations between working/short-term memory and math. In addition, the inclusion of children with clinical disorders other than ADHD in the non-ADHD group was a strength in that it provided more effective control for the presence of these co-occurring conditions in the ADHD group. However, the inclusion of children with and without ADHD may reduce the specificity of findings to either population despite sensitivity analyses suggesting that the results were robust when examining children with ADHD specifically.

Similarly, despite the study's relatively large sample size and evidence that the ADHD and non-ADHD samples were comparable with regard to race/ethnicity, SES, and maternal education level, the majority of the participants in the study identified as White and relatively high maternal education levels were reported (i.e., majority of mothers reported having a bachelor's degree or higher). As such, the findings from the study may not generalize to historically excluded racial minority groups as well as children who have mothers with relatively lower levels of education. Next, this study was cross-sectional, which limits conclusions regarding the direction of relations between our constructs (Thoemmes, 2015) despite (a) experimental evidence indicating that working memory exerts a functional if not causal influence on ADHD behavioral expression (Kofler et al., 2010; Rapport et al., 2009) and other academic skills such as reading (Kofler et al., 2019) and (b) longitudinal evidence that working memory and ADHD symptoms exert a significant influence on the development of math skills (Rennie et al., 2014). However, there is some evidence that relations between working memory and math skills may be bidirectional (Fuhs et al., 2014), and it remains unclear if math performance has a bidirectional relation with ADHD behavioral symptoms in the classroom.

Next, a strength of the study was our ability to fractionate the working memory system into its component processes based on the Baddeley (2007) model. Nonetheless, the central executive can likely be further fractionated into multiple subprocesses such as continuous updating, dual processing, serial/temporal reordering (Fosco et al., 2020), internal focus of attention (Oberauer & Hein, 2012), interference control, and interfacing with long-term memory (Baddeley, 2007), with functions that differ somewhat across conceptual models of working memory. Future research is needed to determine the extent to which one or more of these processes is driving the central executive's association with math despite evidence that it is shared rather than unique subcomponents of the central executive that drive its association with ADHD behavioral symptoms (Fosco et al., 2020). Similarly, future studies may benefit from including additional tasks that require episodic buffer processes to provide a more complete representation of the most recent version of the Baddeley (2017) working memory model, despite recent experimental evidence indicating that the episodic buffer is likely intact in most children with ADHD (Kofler et al., 2017; cf. Alderson et al., 2022). Next, despite the inclusion of practice trials to ensure task comprehension, future research is needed to determine the role of language processes in the association between phonological short-term memory, ADHD, and math (Korrel et al., 2017). Finally, although short-term/working memory abilities explained a substantial proportion of the variance in children's math skills (56%), a nontrivial proportion of individual differences in children's math skills remained unexplained (i.e., 44%). To that end, a more complete model of how working memory impacts math achievement would benefit from consideration of additional factors such as history of math intervention, math anxiety, school climate and quality, reading skills, as well as visual attention, cognitive information processing speed, and strategic/conceptual thinking—abilities that themselves appear affected by working memory abilities based on experimental and longitudinal evidence (e.g., Fosco & Hawk, 2017; Kofler et al., 2010; Tourva et al., 2016). Additional experimental and

longitudinal studies in children with ADHD are required to further examine these interrelations.

Research and Clinical Implications

Taken together, the current results indicate that central executive working memory, phonological short-term memory, and visuospatial short-term memory are significant and approximately equal contributors to math skills, and collectively explain 56% of individual differences in children's math performance. Given these relations, assessment of working and short-term memory may be informative when screening children who present with difficulties in math. Current evidence indicates that growth in working memory relates to growth in math outcomes (Fuchs et al., 2005) and vice versa (Raghubar et al., 2010), suggesting that assessment and intervention in either/both area(s) may prove beneficial for promoting growth across domains. In addition, students with working memory difficulties may benefit from different types of math interventions than students with average working memory (Fuchs et al., 2013), suggesting that working memory abilities may serve as a prognostic indicator when developing math intervention plans. While current evidence-based interventions for math often target core skills such as computational fluency (McKevett & Codding, 2021), instructional review articles have called for more vigorous research in the area of effective instructional practices for math (Hodara, 2011), including more evidence on the link between executive function training and academic achievement (Jacob & Parkinson, 2015). Given the relative inefficacy of ADHD behavioral and medication treatments for improving math and other academic outcomes (Conners, 2002; DuPaul & Eckert, 1997; Van der Oord et al., 2008), alternative approaches to targeting math difficulties in children with ADHD are clearly warranted. Looking forward, combining evidence-based math instruction/intervention with central executive and/or short-term memory training may have the potential for additive/augmentative benefits (Chacko et al., 2014), given the large proportion of variance in math skills explained herein and emerging neurocognitive intervention evidence reviewed above (Singh et al., 2022). At present, however, direct instruction in math skills using evidence-based strategies remains the first-line intervention of choice for children with ADHD and math difficulties (Jitendra et al., 2008; Raggi & Chronis, 2006).

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