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Working memory and short-term memory deficits in ADHD: A bifactor modeling approach

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Abstract

Objective—Attention-deficit/hyperactivity disorder (ADHD) has been associated with large magnitude impairments in working memory, whereas short-term memory deficits, when detected, tend to be less pronounced. However, confidence in these findings is limited due to task impurity combined with methodological and statistical limitations of the current evidence base.

Method—A well-characterized, clinically-evaluated sample of 172 children ages 8–13 years (*M*=10.30, *SD*=1.42; 72 girls; 64% White/non-Hispanic) were administered multiple, counterbalanced working memory tests. Bifactor-(s-1) modeling was used to characterize the presence and magnitude of central executive working memory, phonological short-term memory, and visuospatial short-term memory deficits in pediatric ADHD.

Results—ADHD status was associated with very large magnitude impairments in central executive working memory that are present in most pediatric cases (*d*=1.63–2.03; 75%−81% impaired), and these deficits covaried with ADHD inattentive and hyperactive/impulsive symptom severity based on both parent and teacher report. There was also evidence for a unique, albeit significantly smaller, impairment in visuospatial short-term memory (*d*=0.60; 38% impaired); however, visuospatial short-term memory abilities did not covary with ADHD symptom severity. There was no evidence linking ADHD with phonological short-term memory deficits across either the dimensional or categorical analyses.

Conclusion—These findings provide strong evidence that ADHD is associated with marked central executive working memory deficits that covary with their behavioral symptom presentation across settings. In contrast, visuospatial short-term memory deficits, when present, are likely epiphenomenal, and the most parsimonious conclusion appears to be that phonological short-term memory is intact in pediatric ADHD.

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Ethical Approval: All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed Consent: Informed consent was obtained from all individual participants included in the study.

Keywords

ADHD; working memory; short-term memory; central executive; visuospatial; phonological

Working memory deficits are present in the majority of children with ADHD and have been shown to covary longitudinally and experimentally with ADHD behavioral symptoms (e.g., Karalunas et al., 2017; Kofler et al., 2018). In contrast, short-term memory deficits, when detected, tend to be smaller in magnitude, present in a smaller percentage of cases, and show weaker to nonsignificant associations with ADHD symptoms (Rapport et al., 2013; Martinussen et al., 2005). However, the extent to which short-term memory abilities are intact in pediatric ADHD remains uncertain due to statistical and methodological limitations that characterize the current evidence base as described below (for review see Gibson et al., 2017, 2018). The current study addressed these limitations by applying the bifactor model (Eid et al., 2018a) to isolate latent estimates of working memory (i.e., the central executive), phonological short-term memory (storage/rehearsal), and visuospatial short-term memory (storage/rehearsal) and link them with ADHD both categorically and dimensionally in a large and carefully phenotyped sample of children with and without ADHD.

Working Memory Deficits in ADHD

Working memory refers to the active, top-down manipulation of information held in short-term memory, and includes interconnected functions of the mid-lateral prefrontal cortex that guide behavior via the updating, dual-processing, and temporal/sequential manipulation of internally-held information (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., 2015; Wager & Smith, 2003), the Baddeley (2007) model has considerable empirical support and has been used extensively in the ADHD literature, where it has proven fruitful for advancing our understanding of both the disorder's neurocognitive deficits and the limitations of extant 'working memory' treatment protocols targeted toward this population (for reviews, please see Kofler et al., 2019; Rapport et al., 2013). In the Baddeley (2007) model, working memory includes three functionally and anatomically distinct components: (a) the central executive, or 'working' component of working memory, which is responsible for acting upon information stored in short-term memory; (b) phonological short-term memory, which is responsible for the temporary storage and rehearsal of language-based, verbal/auditory information; and (c) visuospatial short-term memory, which provides temporary storage/rehearsal of visual and spatial information that cannot be coded verbally. Throughout the manuscript, we use the term 'working memory' to refer to the '*working*' (i.e., central executive/active processing) components of the working memory system. Similarly, we use the term 'short-term memory' to refer to the '*memory*' (i.e., temporary storage/rehearsal) components of the working memory system.

Working memory deficits are well established in ADHD (for review see Kasper et al., 2012); however, there remains significant debate regarding the magnitude of these deficits and the extent to which they reflect underlying mechanisms that produce ADHD behavioral symptoms as opposed to reflecting epiphenomenal symptoms or moderating recovery (for review see Chacko et al., 2014). For example, early meta-analytic estimates indicated medium magnitude impairments (*d*=0.55–0.63; Willcutt et al., 2005), which suggest that only 35%−40% of children with ADHD are likely to have working memory impairments based on converting effect sizes into proportion non-overlap (Zakzanis, 2001). Highly similar results were reported in at least two within-subject heterogeneity studies finding that only approximately 30% of children with ADHD were classified as impaired in working memory (Coghill, Seth, & Matthews, 2014; Wahlstedt, Thorell, & Bohlin, 2009). In contrast, more recent meta-analytic evidence indicates very large effect sizes (*d*=2.01–2.15 based on meta-regression) that suggest that up to 85% of children with ADHD have working memory deficits (Kasper et al., 2012). Furthermore, highly similar results were reported in recent heterogeneity studies reporting that 62%−85% of children with ADHD were classified as impaired in working memory (Fosco et al., in press; Karalunas et al., 2017; Kofler, Irwin et al., 2019).

As argued by Fosco et al. (in press), the variability in these reported estimates appears to reflect the challenges inherent in assessing children’s working memory. In particular, studies finding lower effect sizes/impairment estimates were more likely to rely on estimates from single tasks that have been criticized for poor construct validity because they primarily assess short-term memory rather than working memory (e.g., backward digit span; Snyder et al., 2015; Wells et al., 2018). In contrast, studies finding higher effect sizes and impairment estimates were more likely to use multiple tasks that involve active serial/temporal reordering of information from separate short-term storage/rehearsal modalities to generate latent/composite estimates that control for short-term memory (Fosco et al., in press). Because all working memory tasks inherently include demands on one or more short-term memory systems (Baddeley, 2007), failure to control for short-term memory abilities is likely to suppress estimates of working memory deficits to the extent that short-term memory abilities are less- or un-impaired in ADHD as suggested below. The current study addresses this issue via latent estimation of working memory based on multiple, counterbalanced tasks with prominent working memory serial reordering demands but differing short-term memory demands (phonological vs. visuospatial).

Short-Term Memory Deficits in ADHD

Despite recent and compelling evidence that ADHD is associated with impairments in working memory, the extent to which ADHD is associated with impairments in the functionally and anatomically distinct phonological and visuospatial short-term memory systems is less clear. Meta-analytic estimates based primarily on simple span tasks suggest that ADHD may be associated with similar, medium magnitude deficits in phonological and visuospatial short-term memory (*d*=0.55 vs. 0.63 in Willcutt et al., 2005; *d*=0.69 vs. 0.74 in Kasper et al., 2012) and/or smaller phonological than visuospatial short-term memory deficits (*d*=0.47 vs. 0.85 in Martinussen et al., 2005), which correspond to impairment rates of 32% to 50% (Zakzanis, 2001). Simple span tasks are designed to primarily assess short-term memory, and typically involve presenting children with a set of numbers, letters, or spatial locations and asking them to repeat the set in either the same or reversed order.[1] However, because ADHD is also associated with impaired working memory processes, these short-term memory estimates may be inflated because even simple span tasks (and potentially all cognitive tasks) require at least some working memory processes associated with controlled attention (e.g., Engle et al., 1999).

To more precisely evaluate short-term memory abilities in children with ADHD, several studies have adopted a regression-based (e.g., Rapport et al., 2008) or ANCOVA approach (e.g., Dovis et al., 2013) that uses phonological and visuospatial working memory tasks to statistically remove variance attributable to the domain-general central executive (working memory) component of the Baddeley (2007) model. These approaches are based on compelling evidence that the working memory system is characterized by a single central executive controller that operates on the functionally and anatomically separate phonological and visuospatial short-term memory subsystems (Baddeley, 2007; Alloway et al., 2006; Smith et al., 1996). Thus, shared variance across phonological and visuospatial working memory tasks can be attributed to the domain-general central executive (referred to as 'working memory' in the current study), whereas unique variance in each task can be attributed to phonological and visuospatial short-term memory, respectively. Using these methods, Rapport et al. (2008) found that ADHD was associated with very large impairments in working memory (d=2.76), large impairments in visuospatial short-term memory (d=0.89), and medium impairments in phonological short-term memory (d=0.55).

However, there are limitations to the use of residual scores for estimating short-term memory components (Gibson et al., 2017, 2018). For example, because error variance is retained in the residual but not predicted scores by definition, effect sizes for phonological/visuospatial short-term memory may be deflated relative to working memory. In addition, Gibson et al. (2017) demonstrated that the residual phonological and visuospatial scores will correlate with each other to the same degree as the predicted score estimates of working memory, but in the opposite direction. In other words, the residual phonological and visuospatial short-term memory scores will correlate negatively with each other – a finding that appears contradictory to theory and evidence for their structural and functional independence (Baddeley, 2007; Gibson et al., 2017).

To address this limitation, Gibson et al (2018) used phonological and visuospatial immediate free recall (IFR) tasks, and scored children's recall based on established primacy and recency effects, to differentiate between performance attributed to primary memory (i.e., short-term memory) and secondary memory (i.e., working memory). Consistent with regression-based methods, they found that children with ADHD displayed large magnitude impairments in working memory (d=0.73–1.12) but showed small magnitude impairments or did not differ from controls in terms of phonological (d=0.38) or visuospatial short-term memory (d=0.29, *ns*). However, a primary limitation of this method is that it involves explicitly instructing participants to adopt a specific strategy for completing the task, which may impact children's performance and produces relatively high rates of excluded

[1]Children's performance when recalling stimuli in the order presented is often interpreted as short-term memory and their performance when recalling stimuli in reverse order is often interpreted as working memory. However, see Wells et al. (2018) for compelling evidence from child, adolescent, and adult clinical and non-clinical samples indicating that a simple reversal of order does not sufficiently engage central executive working memory processes. Please also see Wells et al. (2018) for a discussion of the distinction between reversal and reordering, such that only the latter sufficiently increases central executive demands despite high face validity for assuming they would function similarly.

participant data (e.g., 21% of the ADHD group in Gibson et al., 2018). To address the limitations of both methods for examining short-term memory in ADHD, Gibson et al. (2017, 2018) called for a bifactor modeling approach to provide latent estimates that maximally distinguish between primary (short-term memory) and secondary memory (working memory). This is the approach used in the current study. As described below, the bifactor model is particularly well suited for this purpose because it provides latent estimates of our constructs of interest, therefore providing a direct test of the extent to which working memory test scores reflect reliable variance attributable to both domain-general working memory processing and domain-specific phonological and visuospatial short-term memory capacity (Eid et al., 2018b).

Current Study

The evidence base at this time suggests that ADHD is associated with large magnitude deficits in working memory but smaller or nonsignificant deficits in phonological and visuospatial short-term memory. However, methodological and statistical issues limit confidence in these findings and no ADHD study to date has maximally fractionated the short-term/working memory system into its functionally and anatomically distinct component processes. The current study is the first to address these limitations and uses bifactor-(s-1) modeling (Eid et al., 2018b) with a large and carefully phenotyped sample of children with and without ADHD to characterize the presence and magnitude of working memory, phonological short-term memory, and visuospatial short-term memory deficits in pediatric ADHD. Building on prior work, we hypothesized that (1) ADHD would be associated with large magnitude impairments in latent estimates of working memory, and that these impairments would be significantly larger than those seen for the short-term memory subsystems; (2) visuospatial short-term memory deficits, if present, would be larger than phonological short-term memory deficits in ADHD (Martinussen et al., 2005); and (3) working memory abilities, but not short-term memory abilities, would covary with continuous estimates of parent- and teacher-reported inattentive and hyperactive symptoms (Chacko et al., 2014; Rapport et al., 2013).

Method

Open Data and Open Science Disclosure Statement

The de-identified dataset (.jasp), annotated results output (including test statistics), and lavaan analysis scripts are available for peer review: [https://osf.io/mvkrc/]. We report how we determined our sample size, all data exclusions, all manipulations, and all measures in the study (Simmons et al., 2012). The work is part of ongoing clinical research investigating neurocognitive mechanisms underlying pediatric attention and behavioral problems. Performance data on the working memory tasks for subsets of the current sample were included in the datasets used for recent studies to investigate conceptually-distinct hypotheses (Groves et al., 2020). We have not previously applied the bifactor model to these task data or modeled/tested short-term memory deficits in ADHD with any participants in the current sample. To our knowledge, this is the first study in the ADHD literature to use multiple tasks and bifactor modeling to fractionate a key neurocognitive system implicated in ADHD (i.e., working memory) into its component processes.

Participants

The sample included 172 children aged 8–13 years (*M*=10.30, *SD*=1.42; 72 girls) from the Southeastern United States, consecutively recruited through community resources from 2015–2019 (Table 1). IRB approval was obtained/maintained, and all parents and children gave informed consent/assent. Sample ethnicity was mixed with 110 White/Non-Hispanic (64.0%), 20 Hispanic/English-speaking (11.6%), 20 African-American (11.6%), 7 Asian (4.1%), and 15 multiracial children (8.7%).

Group Assignment

All children with ADHD and their parents completed a comprehensive psychoeducational and diagnostic evaluation that included a detailed, semi-structured 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 DSM-5 criteria (APA, 2013), and was supplemented with parent and teacher ratings from the Behavior Assessment System for Children (BASC-2/3; Reynolds & Kamphaus, 2015) and ADHD Rating Scale-4/5 (ADHD-4/5; DuPaul et al., 2016). Please see the larger study's preregistration for a detailed account of the comprehensive psychoeducational evaluation and study procedures (https://osf.io/abwms). A psychoeducational report was provided to parents.

Eighty-one children met all of the following criteria and were included in the ADHD group (*n*=81; 32% girls): (1) DSM-5 diagnosis of ADHD Combined (*n*=62), Inattentive (*n*=17), or Hyperactive/Impulsive Presentation (*n*=2) by the directing clinical psychologist based on K-SADS; (2) borderline/clinical elevations on at least one parent and one teacher ADHD subscale; and (3) current impairment based on parent report. All ADHD subtypes/ presentations were eligible given the instability of ADHD subtypes (Valo & Tannock, 2010). Psychostimulants ($n_{prescribed}$=25) were withheld ≥24 hours for testing. To improve generalizability, children with comorbidities were included. Comorbidities reflect clinical consensus best estimates (Kosten & Rounsaville, 1992), and included anxiety (24%), oppositional defiant (10%)[2], autism spectrum (9%), and depressive (5%) disorders. Positive screens for reading (15%) and math disability (10%) were defined based on score(s) >1.5 *SD* below age-norms on one or more KTEA-3 Academic Skills Battery reading and math subtests, as specified in DSM-5 (APA, 2013).

The Non-ADHD group comprised 91 consecutive case-control referrals (46 girls) who did not meet ADHD criteria, and included both neurotypical children and children with psychiatric disorders other than ADHD. Neurotypical children (70%) had normal developmental histories and nonclinical parent/teacher ratings and were recruited through

[2]As recommended in the K-SADS, oppositional defiant disorder was diagnosed clinically only with evidence of multi-informant/ multi-setting symptoms. ODD comorbidity is 48% in the ADHD group and 16% in the Non-ADHD group based on parent-reported symptom counts.

community resources. Clinically referred and evaluated children who did not meet ADHD criteria were also included in the Non-ADHD group. These Non-ADHD disorders were included to control for comorbidities in the ADHD group, and included best estimate diagnoses of anxiety (18%), autism spectrum (8%), depressive (3%), and oppositional defiant disorders (1%). None of the clinically-evaluated Non-ADHD cases screened positive for learning disorders in reading; 1 screened positive for a learning disorder in math. The clinically-evaluated Non-ADHD cases did not differ significantly from the ADHD group in the proportion of children diagnosed with anxiety (p=.45), depression (p=.59) or ASD (p=.97); the ADHD group had a higher proportion of ODD cases as expected (p=.03).

Of the Non-ADHD participants, 51 completed an identical evaluation as the ADHD group. Due to funding constraints, the remaining 40 Non-ADHD participants completed an abbreviated screening evaluation that included parent BASC-3, a 1-subtest IQ screener, and detailed developmental, medical, educational, and psychiatric histories. Neurotypical children did not differ significantly based on whether they received a full or abbreviated evaluation in terms of IQ, gender, ethnicity, age, or BASC hyperactivity T-scores (all $p > .28$). The abbreviated subgroup had, on average, slightly lower BASC inattention T-scores (M=48.0 vs. 55.3, $p = .001$) and SES (M=45.5 vs. 53.3, $p = .01$).

Children were excluded if they presented with gross neurological, sensory, or motor impairment; history of seizure disorder, psychosis, or intellectual disability; or non-stimulant medications that could not be withheld for testing. Additional exclusion criteria were added *a priori* for the abbreviated evaluation subgroup because we were unable to clinically evaluate these cases: previous diagnosis of ADHD or other psychiatric disorders, or BASC-3 inattention/hyperactivity T-scores > 1.5 SD above the normative sample mean for age and gender.

Working Memory Tasks

Working memory reordering—The Rapport et al. (2009) computerized working memory tests and their administration instructions are identical to those described in Kofler et al. (2018). These computerized phonological and visuospatial working memory tasks predict hyperactivity (Rapport et al., 2009), attention (Kofler et al., 2010), impulsivity (Raiker et al., 2012), ADHD diagnostic group membership (Tarle et al., 2017), and ADHD-related functional impairments (Friedman et al., 2017; Kofler et al., 2011, 2016). Reliability and validity evidence includes internal consistency (α=.82-.97; Kofler, Sarver et al., 2018), 1- to 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). Internal consistency in the current sample was .81 (phonological) and .87 (visuospatial). Five practice trials were administered before each task (80% correct required).

Both tasks involve serial reordering of characters presented (numbers, black dot locations), and reordering of a target stimulus (letter, red dot location) into the final serial position. The phonological task involved mentally reordering and verbally recalling a jumbled series of sequentially presented numbers and letters (e.g., 4H62 is correctly recalled as 246H). The visuospatial task involved mentally reordering a sequentially presented series of spatial locations based on what color dot appeared in each location (black dots in serial order, red dot last) and responding on a modified keyboard. Six trials were administered at each set size for each task (3–6 stimuli/trial; 1 stimuli/second; 1 second between the final stimuli and the response phase; 1 second between trials). The 24 total trials per task were randomized, then grouped into 2 blocks of 12 trials each, with short breaks between each block (approximately 1 minute; Kofler et al., 2016). Partial-credit unit scoring (stimuli correct per trial) was used to derive performance estimates at each short-term memory load (set sizes of 3 to 6 items per trial) for each task as recommended (8 total variables: phonological memory loads 3–6, visuospatial memory loads 3–6; Conway et al., 2005). Higher scores indicate higher accuracy.

Bifactor-(s-1) Models

The bifactor model was selected *a priori* given our goal of identifying process pure, latent estimates of domain-general working memory and the two domain-specific short-term memory systems (phonological, visuospatial). This decision was guided by the Baddeley (2007) model, which posits a single central executive (working memory) controller that operates on distinct phonological and visuospatial short-term storage buffers. In this model, shared variance across working memory tasks with different stimulus modalities (i.e., phonological vs. visuospatial) is attributed to domain-general working memory (termed the ‘central executive’), whereas unique variance associated with each task is attributed to a domain-specific short-term memory system (termed the phonological and visuospatial ‘storage/rehearsal’ subsystems; for review, see Rapport et al., 2008). 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 (Baddeley, 2007; Alloway et al., 2006; Smith et al., 1996).

Following recommendations for bifactor models by Eid et al. (2018a), the current study used a bifactor-(s-1) structure such that all 8 indicators (VS and PH memory set sizes 3, 4, 5, 6) loaded onto a general factor (i.e., working memory) and a subset of indicators also loaded onto each specific short-term memory factor (i.e., phonological or visuospatial). As required to properly fit the bifactor model and interpret the general factor, one or more items must load onto the general factor but not onto any specific factor (Eid et al., 2018b). These reference facets serve as markers that define the meaning of the general factor (in this case, working memory). To ensure that the general factor reflected domain-general working memory, we selected 2 reference facets: one phonological and one visuospatial (Heinrich et al., 2018). 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 (see Kofler et al., 2010 for empirical support for this conceptualization in an ADHD sample). Exploratory analyses indicated that the pattern and interpretation of results was unchanged when different combinations of reference facets were selected, suggesting robustness of the findings to this methodological decision.

Importantly for our purposes, the general factor is modeled as uncorrelated with the specific factor(s) in the bifactor model, and the specific factors are also modeled as uncorrelated with each other, based on the underlying assumption that an individual's score on an item reflects at least two distinct sources of reliable variance (i.e., attributable to the general factor and the specific factor).[3] This model differs from the traditional hierarchical approach, which assumes that the general factor affects the specific factor, which in turn affects the individual item (Eid et al., 2018a). Thus, the bifactor-(s-1) model allows maximal discrimination between our constructs of interest, therefore providing a direct test of the extent to which working memory test scores reflect reliable variance attributable to both domain-general central executive processing (working memory) and domain-specific phonological and visuospatial storage/rehearsal (short-term memory) processes (Eid et al., 2018b). By fractionating test performance into reliable variance associated with all three primary components of the Baddeley (2007) model, this approach provides the ideal test of the extent to which ADHD is associated with specific short-term memory deficits when accounting for their well-documented impairments in working memory, as recommended (Gibson et al., 2017, 2018).

Data Analysis Overview

Analyses were conducted using structural equation modeling (SEM) via the R package lavaan (Rosseel, 2012) as implemented in JASP v.0.10.2 (JASP Team, 2019). The software Omega v2 (Watkins, 2017) was used to assess the multidimensionality, construct reliability and replicability, and explained common variance of the Tier 2 bifactor model. Our primary analyses are organized into two analytic Tiers. In the first Tier, we built the single-factor model (all 8 task performance indicators loading onto a single 'working memory' factor). In Tier 2, we added the phonological and visuospatial short-term memory specific factors (Figure 1).

Tiers 1 and 2 each included three models: First, we built the short-term/working memory measurement model to evaluate model fit. Second, we tested the extent to which ADHD diagnostic status was associated with impairments in each short-term/working memory component. This structural model involved adding ADHD status (no/yes) to each model and then correlating it with the short-term/working memory factor(s). Because the ADHD grouping variable was dichotomous, we then converted the standardized correlation coefficients (*r*) to Cohen's *d* effect sizes (Hayes, 2009) and the proportion of non-overlap (Zakzanis, 2001) to aid interpretation. The 'proportion of non-overlap' statistic estimates the proportion of ADHD cases that fall outside of the Non-ADHD range and thus provides an estimate of the percentage of ADHD children with impairments in each short-term/working memory component (Zakzanis, 2001); these estimates tend to align closely with values obtained from within-subject/heterogeneity methods for defining neurocognitive impairment rates in ADHD as seen above.

[3]Correlating specific factors with each other is permissible in bifactor-(s-1) models (Heinrich et al., 2018). We decided *a priori* to model our phonological and visuospatial short-term memory specific factors as uncorrelated based on their structural and functional independence as reviewed above. Exploratory analyses allowing them to covary indicated that they were not significantly correlated, $r=.17$, $p=.40$, and that adding this pathway did not improve model fit $\Delta\chi^2$ [1]=0.48, $p=.49$.

Third, we replaced the dichotomous ADHD status variable with continuous estimates of parent- and teacher-reported attention problems and hyperactivity/impulsivity (age and gender normed BASC-3 T-scores, allowed to correlate with each other) to probe the extent to which children's abilities in each short-term/working memory component covary with ADHD symptom severity. We then used the test for dependent correlations as implemented in the R package cocor (Diedenhofen & Musch, 2015) to test whether the associations between each short-term/working memory component and ADHD diagnosis/symptom severity differed significantly in magnitude (e.g., do children with ADHD have larger impairments in working memory than they have in visuospatial short-term memory?).

For all confirmatory models, absolute and relative fit were tested. Adequate model fit is indicated by CFI and TLI ≥ .90, and RMSEA ≤ .10. The χ^2 difference test was used to evaluate nested model fit; lower chi-square values indicate the preferred model (Satorra & Bentler, 2010). 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., 2016b). Explained common variance (ECV) indicates the proportion of reliable variance explained by each factor. The percentage of uncontaminated correlations (PUC) is used to assess potential bias from forcing unidimensional data into a multidimensional 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., 2016a). 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 < |1| except phonological set size 3: kurtosis [SE] = 3.05 [0.37]). Delta scaling with maximum likelihood estimation with robust standard errors (MLR) were therefore used to handle non-normality (Kline, 2016). Standardized residuals were inspected for magnitude (all positive and ≤ 1, indicating no evidence of localized ill fit). Directionality of parameter estimates were inspected.

Results

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 172, power (1- β) ≥ .80, α=.05, and 10,000 simulations per model run. Briefly, 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 Tier 1 analyses, results indicated that our model is powered to detect standardized factor loadings ≥ .52, which falls well below the loadings for these tasks in previous factor analytic studies (e.g., Kofler, Irwin et al., 2018). For the Tier 2 analyses, our model is powered to detect associations of $r \geq .24$

between ADHD status and each short-term/working memory component. Finally, based on the Rweb quantpsy utility, for α=.05 and 52 degrees of freedom for our most complex model, our *N*=172 is powered to differentiate between an adequate (RMSEA=.05) and poor fitting model (RMSEA=.10) at power (1- β) = .98. Thus, the study is sufficiently powered to address our primary aims (Preacher & Coffman, 2006).

Preliminary Analyses

All parent and teacher ADHD rating scale scores were higher for the ADHD relative to Non-ADHD group as expected (Table 1). The ADHD group demonstrated impairments on all 8 phonological and visuospatial working memory performance variables (d = 0.87–1.65; all p<.001). There was no significant evidence to indicate between-group differences in socioeconomic status (p=.44), whereas the ADHD group was slightly younger (10.1 vs. 10.5; p=.05) and had slightly lower IQ estimates (102.7 vs. 107.7, p=.02). Age, gender, and SES were controlled in all analyses; the pattern and interpretation of results is unchanged if these covariates are removed.[4] 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; Kofler et al., 2016). In other words, covarying IQ would preclude conclusions regarding ADHD as a neurodevelopmental disorder by fundamentally changing our grouping variable, and remove significant variance associated with the outcomes of interest (Ackerman, Beier, & Boyle, 2005; Dennis et al., 2009).

Tier 1: Working Memory Deficits in ADHD

Model fit—In Tier 1, all 8 indicators loaded significantly onto the domain-general working memory factor (β=.40-.81, all p<.001) and the model showed adequate fit (Table 2).

ADHD diagnostic status—Adding ADHD status (no/yes) to the single-factor model revealed that children with ADHD demonstrated very large magnitude impairments in working memory (r=.71, p<.001; Table 3 top/right triangle). An r of .71 corresponds to a Cohen's d of 2.03 and an 81% population non-overlap estimate, suggesting that approximately 81% of children with ADHD have impaired working memory abilities as defined by scores that fall below the Non-ADHD range.

ADHD symptom severity—With continuous estimates of ADHD symptoms added to the model (replacing the dichotomous ADHD status indicator), better developed working memory was associated with lower ADHD inattentive and hyperactive/impulsive symptom severity based on both parent and teacher report (r= −.25 to −.30, all p<.009; Table 3 top/right triangle).

[4]In the Tier 2 models reported below, older age predicted better working memory abilities (β=.38-.41, p<.001) and slightly lower likelihood of ADHD group membership (β=.16, p=.03). Male gender predicted greater likelihood of ADHD group membership (β=.20, p=.008) and better visuospatial short-term memory abilities (β=.27, p=.02), whereas lower SES predicted less well developed visuospatial short-term memory abilities (β=.31-.33, p<.001). Age, gender, and SES were not correlated significantly with the BASC-3 age- and gender-normed parent/teacher-reported ADHD symptom severity scores (all p>.07).

Tier 2: Short-Term Memory Deficits in ADHD

In Tier 2, we built the working memory/phonological short-term memory/visuospatial short-term memory bifactor-(s-1) model. This involved adding the phonological and visuospatial short-term memory specific factors to the Tier 1 model (Figure 1). Results indicated excellent model fit, all indicators loaded significantly onto their hypothesized factor(s), and model fit was significantly improved relative to the Tier 1 single-factor model (all p<.001; Table 2). The proportion of uncontaminated correlations was <.70, supporting the multidimensionality of the data (PUC=.68; Rodriquez et al., 2016; Watkins, 2017). Reliability was high for the general factor (ω=.88) and both specific factors (ωs=.76–84). Total variance explained by the model was 53%, whereas unique (unexplained) variance was 47%, highlighting task impurity and the importance of using multiple indicators for valid assessment of neurocognitive processes (i.e., 47% of the variance in test scores was not attributable to the constructs of interest). The general working memory factor explained 75% of the common variance (ECV=.75) vs. 25% for the specific factors (phonological ECV = .12, visuospatial ECV = .13), indicating that the short-term memory factors explained modest but substantive portions of the reliable variance in task performance (Canivez, 2015).

ADHD diagnostic status—The association between ADHD and working memory deficits remained very large (r=.63, p<.001, d=1.63, population nonoverlap=75%; Table 3 bottom/left triangle). In addition, ADHD was associated with a unique impairment in visuospatial short-term memory (r=.29, p=.004; Cohen's d=0.60). This effect size suggests that approximately 38% of children with ADHD exhibit impaired visuospatial short-term memory (Zakzanis, 2001). In contrast, there was no evidence for a unique impairment in phonological short-term memory (r=.14, p=.27; d=0.28, 20% population non-overlap). Results of the tests of dependent correlations revealed that ADHD status showed a significantly higher association with working memory than it did with both phonological and visuospatial short-term memory (p<.0001), which did not differ (p=.15; WM>PH=VS).

ADHD symptom severity—Similar to the Tier 1 results, better-developed working memory was associated with lower ADHD symptom severity based on both parent and teacher report (r= −.28 to −.35, all p<.002; Table 3 bottom/left triangle). In contrast, neither phonological short-term memory (r= −.25 to .26, all p>.10) nor visuospatial short-term memory (r= −.01 to .12, all p>.30) were associated with ADHD symptom severity based on parent or teacher report. Results of the tests of dependent correlations are as follows: In terms of associations with parent- and teacher-reported hyperactive/impulsive symptoms, working memory showed significantly stronger relations relative to both phonological and visuospatial short-term memory (all p<.004), which did not differ (both p>.18; WM>PH=VS). In terms of associations with parent- and teacher-reported attention problems, visuospatial short-term memory showed significantly weaker relations relative to both working memory and phonological short-term memory (all p<.04); the difference between working memory and phonological short-term memory did not reach significance for parent- (r= −.28 vs. −.25; p=.77) or teacher-reported attention problems (r= −.31 vs. −.12; p=.07; WM=PH>VS).[5]

Taken together, the Tier 1 and 2 results confirm previous findings of large magnitude working memory deficits in pediatric ADHD (d=1.62–2.03), with deficits apparent in approximately 75%−81% of these children and evidence that working memory difficulties covary with greater parent- and teacher-reported inattentive and hyperactive/impulsive symptoms. In addition, a sizable minority of children with ADHD (38%; d=0.60) exhibit an additional impairment in visuospatial short-term memory, but these difficulties were not associated with ADHD symptoms based on either parent or teacher report, suggesting that visuospatial short-term memory difficulties are likely epiphenomenal rather than contributory to core ADHD behavioral symptoms. Finally, there was no categorical or dimensional evidence to support a unique impairment in phonological short-term memory.

Discussion

The current study was the first to apply the bifactor model to the study of short-term and working memory in pediatric ADHD in a large and carefully phenotyped sample of children with and without ADHD. Overall, the current findings indicate large magnitude working memory deficits in pediatric ADHD (d=1.62–2.03) that covary with both inattentive and hyperactive/impulsive symptom severity, with population nonoverlap estimates suggesting that working memory deficits are present in approximately 75%−81% of these children. These estimates are highly consistent with meta-analytic ‘best case’ estimates based on tasks with high central executive demands (d=2.01–2.15, 81%−84% impaired; Kasper et al., 2012), as well as with studies using latent or composite estimates (d=1.41–1.67; 62%−85%; Karalunas et al., 2017; Kofler, Irwin et al., 2019). At the same time, these effect sizes and impairment estimates are significantly higher than omnibus meta-analytic estimates of d=0.55–0.74 (Kasper et al., 2012; Willcutt et al., 2005) and impairment estimates of approximately 30% (Coghill, Seth, & Matthews, 2014; Wahlstedt, Thorell, & Bohlin, 2009). As argued by Fosco et al. (in press), the discrepancy between these ranges likely reflects the use of latent/composite estimates vs. relying on single tasks that have been criticized for suboptimal construct validity due to placing insufficient demands on the central executive ‘working’ component of working memory and/or that confound measurement of working memory and short-term memory (Snyder et al., 2015).

Of primary interest in the current study was the extent to which pediatric ADHD is associated with unique impairments in the temporary storage and rehearsal of information (i.e., short-term memory). Understanding the presence and prevalence of short-term memory deficits in ADHD is critical given that they are the primary targets of extant ‘working memory’ training protocols for ADHD (for review see Rapport et al., 2013). Previous evidence suggested that short-term memory may be relatively less impaired than working memory in pediatric ADHD and that such deficits, if present, do not appear to covary with ADHD symptom severity (for review, see Chacko et al., 2014). However, the veracity of

[5]Exploratory analyses using the ADHD-RS-4/5 ADHD subscale T-scores (Attention Problems, Hyperactivity/Impulsivity) instead of the BASC-2/3 were added during the peer review process. Results for the *ADHD symptom severity* analyses were highly consistent with those reported in both Tiers 1 and 2. Specifically, working memory correlated significantly with all 4 ADHD-RS-4/5 subscales in Tier 1 (r= −.19 to −.38, p<.05) and Tier 2 (r= −.24 to −.41, p<.01). In Tier 2, neither phonological short-term memory (r= −.23 to .25, all p>.09) nor visuospatial short-term memory (r= −.02 to .07, all p>.59) were associated with ADHD symptom severity based on parent or teacher report. We also explored the relations between the BASC and ADHD-RS and found that same informant/subscale correlations between the ADHD-RS and BASC in the current study were r = .63-.80 (all p< .001).

these conclusions was limited due to methodological and statistical limitations with the tasks and methods used to estimate phonological and visuospatial short-term memory in most previous studies (Gibson et al., 2017, 2018). By applying the bifactor model (Eid et al., 2018a), we were able to address these limitations and fractionate the working memory system to obtain latent, process-pure estimates of both phonological and visuospatial short-term memory.

Interestingly, ADHD appears to be uniquely associated with impairments in visuospatial short-term memory that are present in about 1/3 of pediatric ADHD cases (d=0.60). This finding is highly consistent with the meta-analytic estimate of d=0.63 for visuospatial working memory obtained primarily from tasks that challenge visuospatial storage/rehearsal (Willcutt et al., 2005), and extends prior findings via improved control for domain-general working memory abilities. Importantly, however, it is unlikely that visuospatial short-term memory deficits, when present, are contributing to the phenotypic expression of ADHD inattentive or hyperactive/impulsive behavioral symptoms. This conclusion is based on the current finding that visuospatial short-term memory was not associated with parent or teacher perceptions of ADHD inattentive or hyperactive/impulsive behavior. Although correlation does not equal causation, it is a necessary prerequisite, and as such the current findings suggest that visuospatial short-term memory deficits are likely epiphenomenal to the inattentive and hyperactive/impulsive behaviors that characterize ADHD (Coghill et al., 2014). To that end, the current findings also suggest that attempts to improve visuospatial short-term memory are unlikely to produce meaningful changes in parent and teacher perceptions of core ADHD behavioral symptoms given that these domains do not appear to be significantly related (Rapport et al., 2013), although of course this conclusion is speculative because the current study did not assess intervention effects. At the same time, it would be premature to conclude that visuospatial short-term memory deficits are unimportant for understanding ADHD. That is, despite its lack of association with core ADHD behavioral symptoms, visuospatial short-term memory deficits may be an important contributor to impairments in peer, family, and/or academic functioning for these children. For example, prior work has linked visuospatial memory with ADHD-related social difficulties (Kofler et al., 2011) and underachievement in reading and math (Sarver et al., 2012); however, the extent to which these associations are attributable specifically to visuospatial short-term memory, as opposed to uncontrolled domain-general working memory processes, remains unknown.

Finally, ADHD does not appear to be associated with a unique deficit in phonological short-term memory. This finding was consistent across categorical and dimensional indicators of ADHD, and suggests that phonological short-term memory is likely intact in most children with ADHD. In this context, it is likely that prior findings of medium magnitude phonological working memory deficits in ADHD (Kasper et al., 2012; Willcutt et al., 2005) likely reflect domain-general impairments rather than impairments specific to the phonological system. Given that ADHD has been associated with impairments on tests intended to assess a broad range of constructs (Willcutt et al., 2005), identifying neurocognitive components that are intact in pediatric ADHD is important for improving our understanding of the mechanisms and processes that underlie – and do not underlie – the disorder’s heterogeneous behavioral presentation (Kofler et al., 2019). For example, Raiker and colleagues reported that pediatric ADHD may be associated with a strength in motor speed (Raiker et al., 2017) and intact reward sensitivity (Tenenbaum et al., 2018). Similarly, we have found that ADHD is likely not associated with impairments in set shifting (Irwin et al., 2019), response speeds (Kofler et al., 2016), or episodic buffer processes (Kofler, Spiegel et al., 2018) based in part on a subset of the current sample. In practice, identifying and harnessing these children's intact cognitive abilities from a strengths-based perspective – in addition to remediating and/or accommodating their deficits – is likely to promote optimal functioning for children with ADHD (Dvorsky & Langberg, 2016).

Limitations

The unique contribution of the current study was its latent assessment of all three primary components of the working memory system in a large and carefully phenotyped sample of children with and without ADHD. Additional strengths of the study include the use of multiple, well-validated tests and bifactor modeling that maximally isolated reliable variance associated with each short-term/working memory component. At the same time, several caveats merit consideration when interpreting results. Our estimates of short-term memory were derived from tasks with prominent executive components (storage + processing). Thus, although results were generally consistent with findings from alternative assessment methods (e.g., simple span, immediate free recall; Dovis et al., 2013; Gibson et al., 2018), it remains possible that short-term memory deficits would be detected/larger on tasks that require simple storage without active mental manipulation of the internally-stored information, although at the same time such tasks would be expected to significantly underestimate working memory (Wells et al., 2018). Similarly, the current study did not evaluate the ability to maintain information in short-term memory over extended durations (Bolden et al., 2012) or assess the episodic buffer. The episodic buffer was added to the Baddeley (2012) model relatively recently and is responsible for the temporary storage of bound information (e.g., visual + verbal). However, prior work suggests that the episodic buffer is likely intact in pediatric ADHD (Alderson et al., 2015; Kofler, Spiegel et al., 2018). Approximately 30% of our ADHD sample was prescribed stimulant medication, which was somewhat lower than epidemiological estimates and may have dampened association magnitudes when juxtaposing short-term/working memory performance obtained off medication with parent/teacher perceptions that may be influenced by medication. Effect sizes for short-term/working memory links with ADHD symptoms may be further blunted by measuring cognitive abilities and overt behaviors in different settings, and these cross-sectional associations disallow causal attributions.

Clinical and Research Implications

Taken together, the current study provides evidence that ADHD is associated with impairments in both working memory and visuospatial short-term memory, but not phonological short-term memory. By addressing statistical limitations associated with previous methods used to estimate these abilities in ADHD, we were able to more precisely isolate performance attributable to each of the three primary components of the Baddeley (2007) model. Importantly, working memory deficits appear to be present in upwards of 3 out of every 4 ADHD cases and covary with their ADHD symptom severity based on both parent and teacher report. Combined with longitudinal and experimental evidence (e.g., Karalunas et al., 2017; Rapport et al., 2009; Patros et al., 2017), the evidence base at this time implicates working memory as a core mechanism that is involved, at least in part, in the phenotypic expression of ADHD behavioral symptoms. In contrast, visuospatial short-term memory deficits were present in fewer ADHD cases and did not covary with ADHD symptom severity. This pattern suggests that visuospatial short-term memory deficits, when present, are likely epiphenomenal to the inattentive and hyperactive/impulsive behaviors that characterize ADHD. When combined with meta-analytic evidence that current ADHD 'working memory' training protocols largely target short-term memory as opposed to working memory (Rapport et al., 2013), the current findings provide further insight into *why* these training protocols fail to reduce ADHD symptomology in well-controlled studies. Nonetheless, future work is needed to determine the extent to which visuospatial short-term memory deficits contribute to the heterogeneous pattern of functional impairments associated with ADHD (Sarver et al., 2012).

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Key Points

Question

Most children with ADHD have impairments in working memory. However, it is unclear whether they also have reduced short-term memory capacities.

Findings

Most children with ADHD have intact short-term memory abilities. In contrast, most children with ADHD exhibit marked impairment in working memory, and only working memory abilities are related to ADHD inattentive and hyperactive/impulsive symptom severity.

Importance

These findings further implicate working memory deficits in the behavioral symptoms that define ADHD. In contrast, these findings suggest that reduced short-term memory capacity is not a viable candidate for explaining why children with ADHD have difficulties with attention and impulse control/hyperactivity.

Next Steps

Despite not being implicated in core ADHD behavioral symptoms, it is possible that individual differences in short-term memory capacity among children with ADHD may help explain the heterogeneity in functional impairments associated with the disorder.

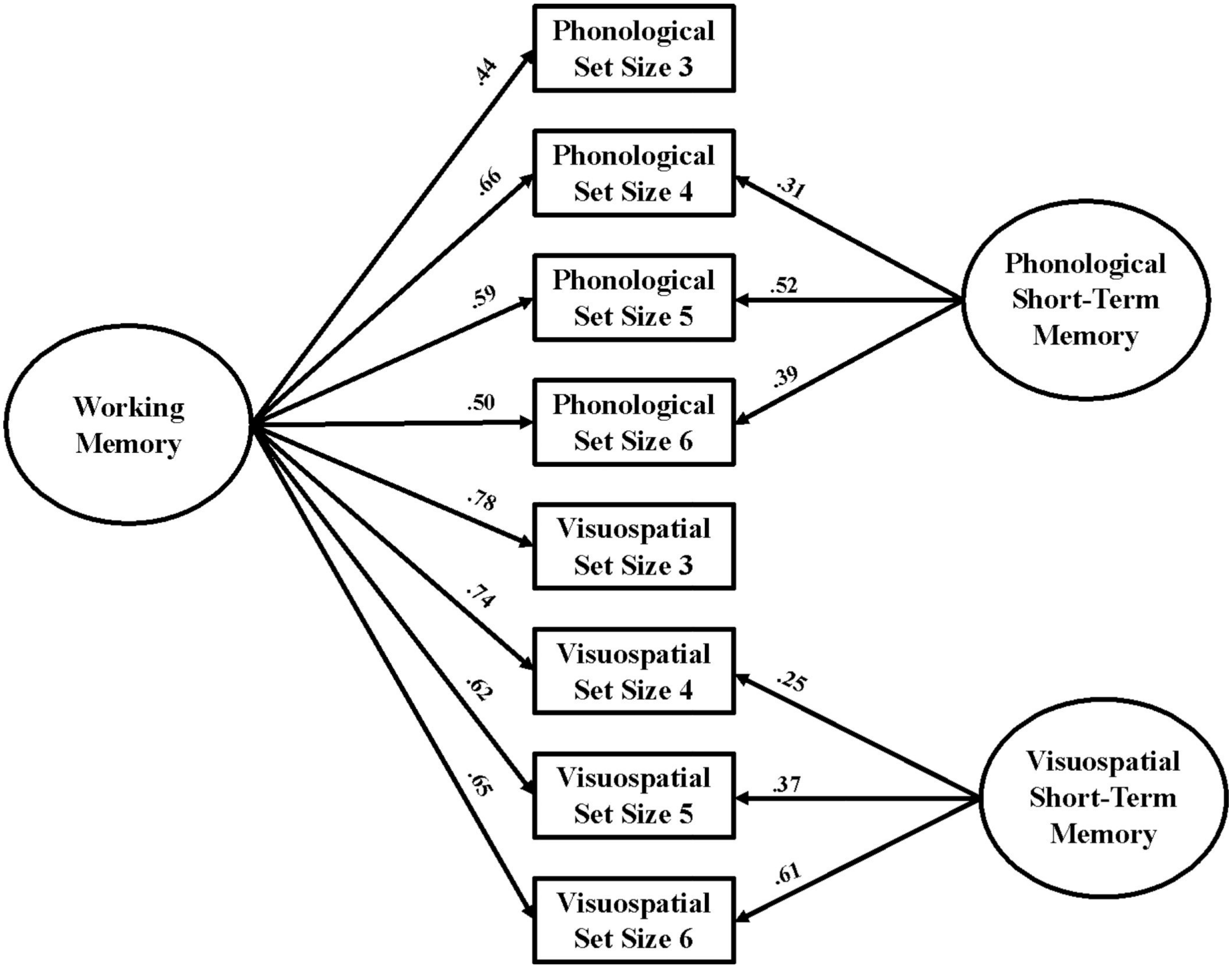

Figure 1.

Bifactor-(s-1) model of central executive working memory (general factor) and short-term memory (phonological and visuospatial specific factors). Standardized loadings are shown (all p<.02). Age, gender, and SES are controlled but not depicted for clarity.

Table 1.

Sample and Demographic Variables

Variable	ADHD (N=81)		Non-ADHD (N=91)		Cohen's *d*	*p*	*Possible Range*	*Obtained Range*
	M	***SD***	***M***	***SD***				
Gender (Boys/Girls)	55/26		45/46		--	.01	--	--
Ethnicity (AA/A/C/H/M)	11/0/58/8/4		9/7/52/12/11		--	.03	--	--
Age	10.07	1.45	10.50	1.37	−0.32	.05	8.00–13.92	8.25–13.25
SES	46.72	12.08	48.13	11.86	−0.12	.44	8–66	20–66
FSIQ (Standard Scores)	102.74	15.52	107.68	12.32	−0.40	.02	43–157	80–135
ADHD Symptoms								
BASC-2/3 Attention Problems (T-scores)								
Parent	67.41	7.87	55.56	11.45	1.04	< .001	10–120	36–82
Teacher [1]	63.72	8.52	55.75	10.76	0.74	< .001	10–120	34–83
BASC-2/3 Hyperactivity/Impulsivity (T-scores)								
Parent	69.17	12.70	54.98	11.35	1.25	< .001	10–120	38–95
Teacher [1]	62.12	13.94	53.56	12.03	0.71	.001	10–120	40–99
ADHD-RS-4/5 Attention Problems (T-scores)								
Parent	66.45	6.26	56.19	10.33	1.19	< .001	37–77	37–77
Teacher [1]	64.75	7.99	51.57	8.99	0.86	< .001	37–77	37–77
ADHD-RS-4/5 Hyperactivity/Impulsivity (T-scores)								
Parent	64.75	7.49	54.82	9.26	1.17	< .001	37–77	43–77
Teacher [1]	66.83	9.70	50.35	9.42	0.68	< .001	37–77	43–77
Working Memory Task Performance								
Phonological Set Size 3	2.70	0.36	2.86	0.19	0.87	< .001	0.00–3.00	1.70–3.00
Phonological Set Size 4	3.21	0.64	3.70	0.31	1.60	< .001	0.00–4.00	1.50–4.00
Phonological Set Size 5	3.68	0.84	4.37	0.51	1.36	< .001	0.00–5.00	1.67–5.00
Phonological Set Size 6	3.18	1.11	4.11	1.07	0.87	< .001	0.00–6.00	0.33–6.00
Visuospatial Set Size 3	1.88	0.66	2.48	0.36	1.65	< .001	0.00–3.00	0.17–3.00
Visuospatial Set Size 4	2.23	0.93	3.15	0.62	1.48	< .001	0.00–4.00	0.17–4.00
Visuospatial Set Size 5	2.39	1.04	2.39	1.04	1.01	< .001	0.00–5.00	0.50–5.00

Variable	ADHD (N=81)		Non-ADHD (N=91)		Cohen's *d*	*p*	*Possible Range*	*Obtained Range*
	M	***SD***	***M***	***SD***				
Visuospatial Set Size 6	2.05	0.82	2.05	0.82	1.25	< .001	0.00–6.00	0.33–5.67

Note.

[1]Teacher BASC data was missing for 28 of the neurotypical children who completed the abbreviated assessment (*n*=63 Non-ADHD cases for these comparisons).

Working memory task performance is measured in stimuli correct per trial. BASC = Behavior Assessment System for Children. Ethnicity: AA = African American, A = Asian, C = Caucasian Non-Hispanic, H = Hispanic, M = Multiracial. FSIQ = Full Scale Intelligence (WISC-V Short Form), SES = Hollingshead socioeconomic status.

Table 2.

Measurement models

Model	CFI	TLI	RMSEA (90%CI)	SRMR	χ^2 [df]	$\Delta\chi^2$ [df]	ω	ωs	ECV	PUC	H
Tier 1											
Working memory single-factor	.91	.88	.09 (.07–.11)	.06	118.48 [51] $p < .001$	--	--	--	--	--	--
Tier 2											
Short-term/working memory bifactor-(s−1)	.97	.95	.06 (.03–.09)	.05	59.21 [37] $p = .01$	59.27 [14] $p < .001$	.88	.76 (PH) .84 (VS)	.75 (WM) .12 (PH) .13 (VS)	.68	.86

Note: Model fits were highly similar for the structural models and are not depicted here but can be found on the study's OSF site (linked in the Method section), which also presents individual item-factor loadings for all models. Omega (ω) and all columns to its right are only computed for bifactor models. PH = phonological short-term memory, VS = visuospatial short-term memory, WM = working memory (central executive). CFI = comparative fit index, ECV = explained common variance, H = construct replicability, ω = omega total (general WM factor), ωs = omega subscale (specific STM factors), PUC = percent of uncontaminated correlations, RMSEA = root mean square error of approximation, SRMR = standardized root mean square residual, TLI = Tucker-Lewis index.

Table 3.

Latent correlations of each short-term/working memory component with ADHD status and continuous ADHD symptoms.

		WM	VS STM	PH STM	ADHD No/Yes	HYP Parent	ATN Parent	HYP Teacher	ATN Teacher	Age	Sex	SES
1.	Working Memory	--	--	--	**.71 *****	**-.30 *****	**-.29 *****	**-.25 ****	**-.27 ****	.46 ***	.10, *ns*	.11, *ns*
2.	Visuospatial Short-Term Memory	.00	--	--	--	--	--	--	--	--	--	--
3.	Phonological Short-Term Memory	.00	.00	--	--	--	--	--	--	--	--	--
4.	ADHD Status (No/Yes)	**.63 *****	.29 **	.14, *ns*	--	−.51 ***	−.51 ***	−.31 ***	−.39 ***	.16 *	−.20 **	.05, *ns*
5.	Hyperactivity T-score (Parent)	**-.32 ****	-.01, *ns*	.02, *ns*	−.51 ***	--	.66 ***	.39 ***	.44 ***	−.04, *ns*	.06, *ns*	−.12 †
6.	Attention Problems T-score (Parent)	**-.28 ****	.02, *ns*	-.25, *ns*	−.51 ***	.66 ***	--	.27 ***	.57 ***	.10, *ns*	−.14 †	−.12, *ns*
7.	Hyperactivity T-score (Teacher)	**-.35 *****	.12, *ns*	.26, *ns*	−.31 ***	.39 ***	.28 ***	--	.53 ***	−.04, *ns*	−.05, *ns*	−.11, *ns*
8.	Attention Problems T-score (Teacher)	**-.31 *****	.10, *ns*	-.12, *ns*	−.39 ***	.43 ***	.57 ***	.53 ***	--	−.05, *ns*	−.16 †	−.14 †
9.	Age	.41 ***	.20, *ns*	.18, *ns*	.16 *	−.04, *ns*	.10, *ns*	−.04, *ns*	−.05, *ns*	--	.08, *ns*	.04, *ns*
10.	Sex (Female/Male)	−.03, *ns*	.27 *	.28 †	−.20 **	.06, *ns*	−.14, *ns*	−.05, *ns*	−.16 †	.08, *ns*	--	.03, *ns*
11.	Socioeconomic Status	−.03, *ns*	.31 **	.29 †	.05, *ns*	−.12 †	−.12, *ns*	−.11, *ns*	−.14 †	.04, *ns*	.03, *ns*	--

Note: The left/bottom triangle reflects associations with the working memory/short-term memory bifactor-(s−1) model (Tier 2). The top/right triangle reflects associations with the single-factor working memory model (Tier 1). The internal boxes highlight the associations of primary interest in the current study (significant correlations bolded). The correlations between working memory (general factor) and phonological/visuospatial short-term memory (specific factors) are set as .00 as required for bifactor modeling. The specific factors were also modeled as uncorrelated based on theory; exploratory analyses indicated that allowing them to correlate did not improve model fit, $\Delta\chi^2$ [1]=0.48, p=.49, and as expected that they did not correlate significantly, r=.17, p=.40. ADHD status's associations with the attention problems/hyperactivity T-scores are based on zero-order correlations (ADHD status was not included in any models with the continuous attention problems/hyperactivity T-scores).

† $p \leq .10$

* $p < .05$

** $p \leq .01$

*** $p \leq .001$